

Review of

*ONR's Uninhabited
Combat Air Vehicles
Program*

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NAVAL STUDIES BOARD
NATIONAL RESEARCH COUNCIL

Review of

*ONR's Uninhabited
Combat Air Vehicles
Program*

Committee for the Review of ONR's Uninhabited Combat Air Vehicles Program
Naval Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

Joint Vision 2010¹ addresses the need for achieving military dominance through the application of new operational concepts. For the Department of the Navy, future operational concepts will hinge on a continuance of forward yet unobtrusive presence and the capability to influence events ashore as required. This capability will be enabled by the development and insertion into the forces of new technologies for providing command, control, and surveillance; battlespace dominance; power projection; and force sustainment. For example, unmanned aerial vehicles (UAVs) have recently proven to be valuable operational platforms for providing tactical intelligence by surveillance of the battlefield. To support naval force objectives, the Office of Naval Research (ONR) has established a research program within the Strike Technology Division (Code 351) of the Naval Expeditionary Warfare Science and Technology Department aimed at expanding the operational capabilities of UAVs to include not only surveillance and reconnaissance, but strike and logistics missions as well. This new class of autonomous vehicles, known as uninhabited combat air vehicles (UCAVs), is foreseen as being intelligent, recoverable, and highly maneuverable in support of future naval operations.

Although UCAVs are not seen as a replacement for manned aircraft, the technical vision for UCAVs suggests they could take advantage of emerging technologies in order to provide weaponry and logistics support at a fraction of the cost of current manned systems. Specifically, these emerging capabilities could include (1) autonomous multi-UCAVs and multisensors, as well as cooperative target cueing and automatic target recognition; (2) sea-based multimission vertical takeoff and landing/vertical short takeoff and landing concepts with a real-time, full-scale simulation environment; (3) secure communications and architecture for autonomous intelligent UCAVs; and (4) real-time autonomous mission planning, path planning, contingency planning, and situational awareness for networked UCAVs.

At the request of the Office of Naval Research, the National Research Council established a committee, under the auspices of the Naval Studies Board, to assess the science and technology issues relating to the ONR program for UCAVs (see Appendix A for short biographies of committee members). Specifically, the review was to evaluate ONR's UCAV technology activities, including its vision documents and its science and technology roadmap (in areas of vehicle dynamics, communications, sensors, and autonomous agents) against criteria that would be selected by the committee, such as the relevance for meeting future naval priorities, the cost and time

¹Shalikashvili, GEN John M., USA. 1997. *Joint Vision 2010*. Joint Chiefs of Staff, The Pentagon, Washington, D.C.

scale for its utilization, duplication of effort, and scientific and technical quality. Although the ONR program includes both basic (6.1) and applied (6.2) research efforts relating to UCAVs, the committee was asked to assess those activities under the 6.2 budget category (Appendix B gives the full terms of reference). A previous NRC committee reviewed the basic research activities.²

In preparing its report, the Committee for the Review of ONR's Uninhabited Combat Air Vehicles Program met twice. The first meeting was held December 13-15, 1999, in Irvine, California; it was devoted mainly to briefings by the study sponsor (and the corresponding principal investigators) on the applied research (6.2) activities—including goals, vision, technical roadmaps, and other plans—of the ONR UCAV program. Additionally, representatives from the Defense Advanced Research Projects Agency/U.S. Air Force UCAV program and the Program Executive Office for Cruise Missiles and UAVs (PEO (CU)) briefed the committee on other UAV/UCAV efforts. The committee's second meeting, held January 18-19, 2000, in Washington, D.C., was spent preparing an initial draft report. Additionally, representatives from the Office of the Secretary of Defense (OSD), the Office of the Chief of Naval Operations (OPNAV), and the Naval Air Systems Command (NAVAIR) briefed the committee on related Department of Defense and Department of the Navy UAV/UCAV efforts; the committee believes that these briefings were necessary in order to establish the review criteria (i.e., the relevance for meeting future naval priorities, cost and time scale for utilization, duplication of effort, and scientific and technical quality) for assessing the science and technology issues related to the ONR 351 UCAV program.

The resulting report represents the committee's consensus view on the issues posed in the charge.

²Naval Studies Board, National Research Council. 1999. *1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program*. National Academy Press, Washington, D.C.

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their participation in the review of this report:

John M. Borky, Tamarac Technologies, Inc.,
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Peter R. Worch, Science Applications International Corporation (retired).

Although the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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Executive Summary

At the request of the Office of Naval Research (ONR), the National Research Council established a committee, under the auspices of the Naval Studies Board, to review ONR's uninhabited combat air vehicles (UCAVs) program. The primary program review was held December 13-15, 1999. For program context, a series of briefings by other Department of Defense and Department of the Navy organizations involved in related unmanned aerial vehicle (UAV) and UCAV activities were presented to the committee on January 18-19, 2000. This report is based on the information presented at those meetings and on the committee members' accumulated experience and expertise in military operations, systems, and technology. The Navy UCAV picture is changing rapidly, and this report necessarily reflects the status at the time the information was presented.

EVALUATION OF THE ONR UNINHABITED COMBAT AIR VEHICLES PROGRAM

The ONR UCAV program was started recently within ONR's Strike Technology Division (Code 351) of the Naval Expeditionary Warfare Science and Technology Department to address the future technology requirements of all (UAVs and UCAVs) naval unmanned aerial vehicles in the battlespace. Working with selected contractors,¹ ONR 351 created an ambitious and far-reaching vision of the role of cooperating UAVs in naval warfare, very much in the spirit of network-centric operations.² Unmanned aerial vehicle missions and candidate UAV flight configurations were hypothesized and technology requirements derived and passed down to the contractor technology teams, which surveyed and identified the relevant critical technologies. Based on the maturity of these technologies as assessed by their experts, the teams created technology roadmaps, which provide descriptions and timetables for recommended science and technology (S&T)—i.e., basic research (6.1) and applied research (6.2)—investments to enable the vision to be realized. A systematic top-down process was used throughout.

The quality and credentials of the contractors enlisted were outstanding. All were known experts in their fields: Lockheed Martin Tactical Aircraft Systems for mission analysis; Lockheed Martin Tactical Aircraft

¹The method of and criteria for contractor selection were not presented to the committee.

²Network-centric operations are military operations that exploit state-of-the-art information and networking technology to integrate widely dispersed human decision makers, situational and targeting sensors, and forces and weapons into a highly adaptive, comprehensive system to achieve unprecedented mission effectiveness. See Naval Studies Board, National Research Council. 2000. *Network-Centric Naval Forces: A Transition Strategy for Enhancing Operational Capabilities*. National Academy Press, Washington, D.C., p. 1.

Systems and Bell Helicopter Textron for air vehicles and avionics; GTE Laboratories and Bolt, Beranek, and Newman Technologies for communications and networking; the Naval Research Laboratory (NRL) for sensors; and the Charles Stark Draper Laboratory for intelligent autonomy and autonomous systems.

The 6.2 funding available was limited to about \$150,000 per contract. ONR 351's investment strategy was a low-budget effort and suffered somewhat as a result. As such, it remains a work in progress, with much of the work apparently needing to be completed.

ONR 351's approach to the generation of the vision was quite different from what might be expected from an R&D organization. Rather than extrapolating from the known missions and capabilities of existing or currently planned UAVs (i.e., bottom-up), ONR took a giant leap and envisioned a battlespace of the future filled with UAVs of all kinds, intercommunicating and operating cooperatively in teams, each vehicle completely autonomous and having no real-time interaction with humans. In this vision of the far future, humans would assign missions, but all the rest of the details of UAV flight—target location and engagement, team coordination, reaction to unexpected events, mission replanning on the fly, and so forth—would be handled entirely by onboard intelligent agent software. While cooperating sensors and weapons are characteristic of network-centric operations, it is generally assumed that real-time interaction with human decision makers is an integral part of the concept. The Office of Naval Research's UAV/UCAV vision takes this another step into the future.

While it is undeniable that autonomy will be increasingly used in military operations as the exponential growth of the enabling computer and software technologies continues, the total autonomy of lethal platforms is a difficult concept to accept today. This ambitious UAV/UCAV vision certainly points in the right direction and is appropriate for an ONR 6.1/6.2 program. However, Code 351, because it omits explicit reference to the inevitable evolution through intermediate levels of real-time, man-machine synergy as the technology is proven capable and trustworthy, does itself a disservice by allowing its vision to appear unrealistic.

To flesh out this vision of the future, ONR, with its principal investigators, postulated and analyzed a number of likely UAV/UCAV missions and identified UCAV system concept design drivers. Only fairly high-performance missions were considered. Based on questions by the committee regarding the validity of certain operational assumptions, it was found that ONR had acted on its own in this matter. Although ONR and its contractors certainly had qualifications in this arena, many relevant Department of the Navy stakeholders (i.e., the Offices of the Chief of Naval Operations for Expeditionary Warfare (N85) and for Air Warfare (N88), the Naval Air Systems Command (NAVAIR), the Naval UAV Executive Steering Group (ESG), and the Marines—the Deputy Chief of Staff for Aviation and the Marine Corps Combat Development Command (MCCDC)) had not yet been involved.

The missions divided fairly naturally into three tiers of performance characterized by the general altitude of the mission, and corresponding classes of UAV were postulated: high, medium, and low. Candidate designs for each class of UAV were created, with examples ranging from a gently maneuvering and long-endurance, high-altitude UAV for collection of situation awareness data to an agile (11-g), short-mission-duration, on-the-deck strike UCAV. Most concepts, including fixed-wing designs, embodied vertical takeoff capabilities suitable for naval shipboard deployment.

From an assessment of this fleshed-out vision, four broad critical technologies were identified: vehicle technology; secure communications and dynamic networking; sensors and sensor systems; and autonomy. Autonomy overlaps the other three areas because each area must exhibit considerable capacity for adaptive behavior and have a control scheme that implements the system's autonomy rules. However, the committee believed that for the future of UAVs in network-centric operations, these four are indeed the broad critical technologies to be addressed, however much autonomy is postulated in the long-term vision.

The individual technology teams then examined each of the critical technologies, specifying the needed capabilities, generally in the form of a useful missions-capability matrix. The committee found no serious deficiencies in the missions-capability matrices. However, the resulting technology development roadmaps fell short of expectations. Clearly unfinished, the roadmaps were general and of very low time resolution (i.e., 5-year intervals were depicted). Lacking details, in their present form they are not yet useful for selecting specific near-term 6.2 projects.

For two of the technologies, vehicles and sensors, the committee concluded that because the missions would be limited to high-performance missions, the resulting vehicles and sensors strongly resembled those carried on manned aircraft, and so the existing or planned capabilities under development for manned aircraft probably would be sufficient for UAV/UCAV and no new capabilities needed to be developed. This is not true for the vehicle avionics or for the sensor information extraction and fusion implied by the vision, but these topics fall largely under communication/networking and autonomy, which were judged to need additional UAV/UCAV attention. The committee believes that while commercial interest in autonomy (e.g., autonomous agents) may dominate many aspects of that technology and the Department of the Navy need only apply the results, the needs of network-centric dynamic networking will not be of great commercial interest, and basic Navy Department- and DOD-sponsored research and development (R&D) will be required.

GENERAL OBSERVATIONS

In spite of the far-reaching nature of its vision and the excellence of its technical team, this small ONR initiative risks being overwhelmed by a number of almost simultaneous and much-better-funded UAV-related efforts within the Department of the Navy, particularly if it chooses—unwisely—to continue alone. The competition for resources comes from, among other things, a procurement for a vertical takeoff and landing tactical UAV (VTUAV) by the Program Executive Office for Cruise Missiles and UAVs (PEO (CU)), awarded in February 2000; a recent Naval Air Systems Command multirole endurance (MRE) UAV broad agency announcement (BAA); the UCAV-N Program, a collaborative DARPA/Navy UCAV advanced technology demonstration (ATD) closely related to a similar DARPA/USAF program; and the newly established Department of the Navy future naval capability (FNC) thrusts, many of which bear directly on UAV/UCAV issues, particularly the FNCs focused on time-critical strike and autonomous operations. If the program is not fully integrated appropriately into the Navy Department community, it will not survive.

In general, the committee had several concerns that bear directly on the ONR program:

- The Department of the Navy needs to better define leadership for setting requirements for UAVs. The current leadership offered by the responsible Navy Department organizations seems to move slowly, envisions only relatively near-term scenarios, and is currently supporting independent multiple thrusts, as yet uncoordinated, without a clear unifying focus on the full future potential of UAVs. The ONR Code 351 program is exploratory in anticipation of requirements, as is appropriate for 6.1/6.2.
- A Department of the Navy UAV/UCAV master plan is needed that is more comprehensive than the current Naval UAV Executive Steering Group plan and that includes S&T components as well as system concepts that explicitly acknowledge the existence of other UAV/UCAV plans and programs outside the Department of the Navy.
- UAV S&T coordination across the DOD community is inadequate. In addition, a DOD S&T roadmap for UAVs is needed, perhaps as a supplement to the current OSD UAV master plan. Stimulated by the NATO action in Kosovo and targeted for completion in June 2000, the current OSD plan addresses DOD-wide timing and funding schedules for the accelerated fielding of UAVs; however, it does not explicitly address S&T issues.
- Software development and cost are increasingly critical for all complex computer-based systems. While everybody uses software, few, if any, software organizations are responsible (or funded) for developing the much-needed software tools and techniques.
- There seem to be no systematic approaches or tools available for partitioning functions between machines (e.g., platforms, flights, C4ISR nodes) and humans or for assessing the military benefits of autonomy. The mathematical and engineering sciences on which autonomous system design and evaluation will be based need development. Autonomy is key, and the military will have to invest to exploit and extend what the private sector will develop.
- Network-centric compatibility must be an integral part of any Department of the Navy UAV/UCAV future vision. Requirements must be developed in the context of a true system-of-systems architecture, with freedom to adjust the structure of the rest of the force to take advantage of UAV/UCAV contributions.

Regarding the assessment requested in the terms of reference, the committee notes the following:

- *Relevance for future naval priorities*—There appears to have been no specific guidance regarding naval priorities. The missions used in forming ONR's future vision for UCAVs seem to be reasonably in line with operations that have occurred recently and that are generally expected in the future. This is not an unusual situation for 6.1/6.2 work.
- *Cost and time scale*—The UAVs projected were at the high-performance, high-cost end of the spectrum: the vision is very futuristic. Not enough information is available to address cost and time issues in any detail. The software needed for intelligent, reliable autonomy will probably be expensive.
- *Duplication*—While many of the technologies involved will undoubtedly experience some duplication in the rather independently evolving UAV/UCAV programs, the aggressive ONR vision of cooperative autonomy appears to be unique in pushing the envelope, which is appropriate for a 6.1/6.2 effort.
- *Quality*—The performance credentials and briefings were of high quality. However, the committee noted that the state of the art for autonomous systems is more advanced than that in the ONR Code 351 program.

RECOMMENDATIONS

Although the committee makes many specific recommendations for improvement throughout the report, its most significant recommendations are summarized below.

With respect to the ONR 351 UCAV program, the committee recommends that ONR should do as follows:

- *Strive to become fully integrated* within the Department of the Navy UAV/UCAV community. The relevant programs—e.g., the ONR 351 UCAV program, the DARPA/Navy UCAV-N, the PEO (CU) VTUAV procurement, the NAVAIR MRE UAV BAA, and the Department of the Navy FNCs—are now largely independent. They should be coordinated according to an agreed-on focus. The Navy should also take advantage of the wide range of results obtained by other Services.
- *Complete the vision* and make it more realistic by recognizing the limited applicability of total (level 5) autonomy, adding an outline of and a timetable for the evolution of human-machine partnerships through a series of intermediate visions. The mathematical and engineering sciences on which autonomous system design and evaluation will be based should be developed.
- *Engage other appropriate Department of the Navy UAV stakeholders* and reexamine their missions to ensure that the UAV/UCAV vision responds to the needs of the whole naval community.
- *Complete the technology roadmaps* after this reexamination.

For the four critical technologies of the ONR 351 UCAV program, the committee recommends the following:

- *Vehicle technology* will evolve without being given special emphasis by an ONR S&T program. Accordingly, ONR should plan to invest only in R&D pertaining to (1) missions that are unique to the Navy, such as landing on a ship or antisubmarine-warfare-related operations support, and (2) overall affordability.
- For *communications and networking*, the commercial sector will not address all issues. ONR should focus on secure communications and dynamic networking directly, as it is doing, while continuing to exploit commercial development whenever possible.
- *Sensors and sensor systems* hardware will evolve without special attention from an ONR S&T program. ONR should focus on software and algorithms for information extraction and fusion rather than on hardware issues. A much-better-focused program of enabling technology development and demonstration than seems to have been put in place so far is essential if limited funds are to produce significant results.
- For *autonomy*, the commercial sector will not address all of the Navy's needs. ONR 6.1/6.2 investments are warranted in several important areas—image understanding, human-machine interaction, multientity control, and metaheuristics, among others—as well as in a systematic examination of the scientific and engineering principles upon which autonomous operations are based. Careful coordination with other R&D programs of the

Navy and the other Services is recommended. ONR should leverage commercial software to emphasize naval-unique applications, demonstrations, and exercises, and it should encourage the formation of a community focused on autonomy that facilitates communication and joint development across industry, government, and academia by means of Navy-sponsored symposia and the like. Finally, the committee recommends that ONR should specifically fund S&T efforts aimed at identifying *and publishing* best practices for the design, development, and evaluation of complex affordable autonomous military systems.

Study Overview

INTRODUCTION

The Office of Naval Research's (ONR's) uninhabited combat air vehicles (UCAVs) program resides within ONR's Strike Technology Division (Code 351) of the Naval Expeditionary Warfare Science and Technology Department. It represents a new thrust, begun in FY99 with an investment of only \$0.93 million of applied research (6.2) funds, and as such currently accounts for only a small fraction of the department's budget. Yet the projected capabilities of all forms of unmanned aerial vehicles (UAVs) are of undeniable interest for future war-fighting capabilities, and this seed activity may well be expected to grow significantly in the near future, given the right circumstances.

In recognition of this potential, Navy interest and investments have increased significantly, with the almost simultaneous creation during the past year of a number of (currently) independent efforts within the Department of the Navy, all addressing UAV/UCAV issues. The specific ONR UCAV program under evaluation here is by far the smallest planned investment. After many years of experience with the Pioneer, the Navy's first UAV, the Program Executive Office for Cruise Missiles and UAVs (PEO (CU)) has awarded a contract for the engineering and manufacturing development of a new vertical takeoff and landing tactical UAV (VTUAV), suitable for operation from ships. Almost simultaneously, the Naval Air Systems Command (NAVAIR) issued a multirole endurance (MRE) UAV broad agency announcement (BAA). In addition, very recently, with the encouragement of the Defense Advanced Research Projects Agency (DARPA) and approval from the Chief of Naval Operations (CNO), active planning began for a joint DARPA/Navy advanced technology demonstration (ATD), known as UCAV-N, which will emphasize issues unique to the Navy but otherwise parallel and complementary to the existing ATD for the DARPA/USAF UCAV. Simultaneously, the Department of the Navy has decided to invest a large portion of its S&T funds in a series of 12 focused technology thrusts known as future naval capabilities (FNCs), several of which address UAV/UCAV issues. Coincidentally, the S&T representatives on the integrated product teams (IPTs) for the two FNCs that bear most directly on UAV/UCAV technology—the time-critical strike and autonomous operations FNCs—are from ONR 351, the same organization that is sponsoring the UCAV program under review here.

SCOPE OF AND APPROACH TO THE ASSESSMENT

The objective of this review was to evaluate S&T issues relating to the ONR 351 program of existing and proposed UCAV 6.2 efforts in terms of their relevance to meeting future naval priorities, the cost and time scale for their utilization, duplication of effort, and overall scientific and technical quality.

The FY99 6.2 funds ONR 351 had invested in UCAV technology were devoted to a systematic, well-executed, top-down planning effort. Supported by well-chosen, experienced systems and technology contractor teams, the planning efforts began with the postulation and analysis of candidate UAV/UCAV missions and goals and an initial partitioning of the solution space into three distinct tiers—high-, medium-, and low-altitude missions. Requirements derived from the resulting vision were provided to contractor teams in each of four critical technology areas (vehicle dynamics, communications/networking, sensors, and autonomy) so they could generate UCAV-critical technology roadmaps. The roadmaps were to identify unresolved UCAV technical issues, and the teams, in consultation with industry and government experts, were to evaluate the maturity of the individual technologies. The technology time lines would provide the basis for establishing specific ONR UCAV 6.2 S&T projects to be undertaken in future fiscal years.

The committee evaluated the planning process and its results; that is, it looked at the quality, completeness, and relevance to future naval priorities of the UCAV vision presented and the validity and completeness of the derived technology requirements and the resulting technology roadmaps. Since the planning process was presented as a work in progress and had not yet resulted in specific FY00 6.2 project proposals, no comments could be made about specific planned projects.

The committee's evaluation of the planning process could only be carried out in the context of all of the related, yet independent, DOD and Department of the Navy UAV activities: the Naval UAV ESG; the PEO (CU) VTUAV procurement; the NAVAIR MRE UAV BAA; an Office of the Secretary of Defense (OSD) Kosovo-inspired UAV roadmap planning activity; the DARPA/USAF and Department of the Navy UCAV ATDs; and the Department of the Navy's FNC thrusts. Accordingly, briefings from DARPA, NAVAIR, OSD, and the Office of the Chief of Naval Operations were solicited to obtain the necessary background information. The committee did not attempt in any way to evaluate or assess these parallel activities, although their potential impact on the ONR UCAV efforts under review are discussed below where appropriate. The implications of these related activities were considered in formulating the recommendations for ONR 351.

FAVORABLE ASPECTS OF THE ONR 351 APPROACH (6.2)

The initiative taken by ONR 351 to create a UCAV vision, mission scenarios, vehicle concepts, and technology roadmaps is significant and commendable. These elements could catalyze an integrated Navy/Marine Corps, Air Force, Army, and DARPA S&T program focused on UAV- and UCAV-enabling technologies, given the right circumstances. Although basic and applied research (6.1 and 6.2) program managers are often criticized for not taking a coherent systems point of view when defining their programs, establishing broad mission and systems requirements is generally not the responsibility of the S&T community. In this case, until very recently, the Department of the Navy's interest in UAVs had been minimal and the Navy Department's requirements community had not yet communicated an official long-term vision of what operational concepts UAV/UCAV technologies could enable in a future network-centric environment or what their advantages would be. The ONR 351 initiative attempted to fill this gap.

A systematic process based on sound systems engineering principles was established and applied top-down to create a UCAV vision. From that vision, which was extremely ambitious and futuristic, requirements were derived and used to develop roadmaps that provide descriptions and timetables for critical technologies.

ONR's definition of the term "uninhabited combat air vehicle" was broader than the usual definition. In ONR usage, the term covered all unmanned aerial vehicles in the battlespace, including those that are known today as UAVs (e.g., Predator, Pioneer, Global Hawk). While this is a reasonable definition, it contrasts with the more common usage, which thinks of UAV as the overall concept and UCAV as a weapons-bearing subset. The future vision presented thus potentially included all forms of UAVs, and ONR 351's term "UCAV" will be replaced

throughout this report by "UAV/UCAV." Other references to UAV or UCAV appear when discussing activities outside the ONR 351 program, and in those cases the usual interpretation of the terms applies.

In addition to defining UAV/UCAV broadly, ONR envisioned complete intelligent autonomy for both the near and far term, because discussions of human participation were minimal or nonexistent. This vision was judged by the committee to be unrealistic. It would perhaps be more reasonable to agree to exploit autonomy to the maximum degree possible at every stage of development, with appropriate levels of human involvement if the technology proves useful, cost-effective, and trustworthy. Trust (i.e., technical and operational reliability and the confidence placed in the reliability) is, of course, the most difficult attribute to achieve but mandatory for any UAV—particularly for UCAVs that are potentially both autonomous and lethal.

Another favorable aspect of the ONR UAV/UCAV planning process was the excellence of the contractors selected to carry out the project. All were highly qualified. Most were well-known experts in their fields, combining broad military experience with commercial know-how. Mission conceptualization and analysis was headed by Lockheed Martin Tactical Aircraft Systems, while the four critical technology areas emphasized—vehicle dynamics, communications and networking, sensors, and autonomy—were supported by Lockheed Martin Tactical Aircraft Systems for fixed-wing and Bell Helicopter Textron for rotary-wing vehicles; GTE Laboratories and Bolt, Beranek, and Newman Technologies for communications and networking; the Naval Research Laboratory (NRL) for sensors; and the Charles Stark Draper Laboratory for intelligent autonomy. A heavy reliance on qualified contractor teams for mission conceptualization and related maps and sequences is familiar today in other contexts through such major procurements as the next-generation surface combatant for the Navy (DD-21) and the DARPA/USAF UCAV ATD.

Although only limited funding was available, probably less than \$150,000 per contract, a good deal of progress was evident. Within the framework of its assumed vision, ONR attempted to identify all UAV/UCAV technology issues in each of the four technology areas and to point out those that were already receiving adequate attention from the community and those that were critical to UCAVs but were not receiving adequate attention. These were then translated into roadmaps, which recommended issues to be addressed in the near, middle, and far term by 6.1/6.2 S&T investments.

ONR identified dynamic communication networking and intelligent autonomy as two of the most significant technical challenges in UAV/UCAV development. It was, in the opinion of the committee, largely correct in its assessment. The program team also concluded that most of the individual sensors already deployed or under development for manned aircraft would be adequate for UAV/UCAV application with little additional UAV-specific effort. What needed attention were the system and software implications of multisensor cooperation, dynamic networking, and autonomy. The committee also supports these conclusions.

AREAS OF CONCERN

For ONR's Strike Technology Division

In spite of the many favorable aspects of ONR 351's UAV/UCAV planning exercise, the primary concern of all the committee members was that both the vision and the technology roadmaps were incomplete.

The vision remains incomplete in several important ways: many critical stakeholders are not represented; the view of the future is extreme in its assumptions about the role of autonomy; only a limited subset of possible UAV/UCAV options was considered; and the consequent structuring of UAV/UCAV configurations into three tiers by altitude may be premature. The resulting vision is not the Department of the Navy's or even ONR's. It is ONR 351's vision, and while it points in the right direction, it needs more Navy and Marine Corps user inputs as well as certification and buy-in from the appropriate requirements and procurement organizations of the Department of the Navy.

As mentioned, the committee believed the vision was unrealistic in projecting complete intelligent autonomy as the goal of all future UAV/UCAV systems. However, many members believed that while this idealized condition may never be realized in practice, it does provide a worthwhile challenge and a useful direction in which to point R&D efforts. Whether the final goal is realistic or not, progress toward it will almost certainly result in

products applicable to the nearer-term human-machine configurations more commonly envisioned. The critical issues and UAV/UCAV technology deficiencies identified by ONR as it considered this ambitious UAV/UCAV vision seem to be generally correct—although certainly incomplete—and will be useful in guiding the selection of focused, near-term 6.1/6.2 technology projects for today and tomorrow.

Clearly, ONR 351 should have showed a greater awareness of the human-machine trade-offs than was evident from the presentations. Another deficiency lies in the fact that only high-performance, relatively expensive options were considered. Many interesting possibilities did not seem to have been included: among those missing were micro-UAVs or the high-dynamic possibilities associated with eliminating the *g*-limitations imposed by human presence in the vehicles. The high-performance vehicles being explored were classified based on mission altitude, and this classification was made an integral part of the vision. This freeze on options was probably premature given the many other factors that should have been considered—stakeholders, other missions, mini/micro or other low-cost possibilities, and so forth. The resulting vision was not unreasonable but was certainly incomplete.

Even if these deficiencies of the ONR vision are disregarded and the vision is judged to be valid, the corresponding roadmaps are incomplete. The individual technology teams appear to be well qualified and did excellent analysis as far as they went, but the roadmaps are clearly unfinished from the standpoint of near-term details. Much of this was no doubt the result of the constraints on time and funding. The roadmaps, and indeed the vision itself, are clearly a work in progress.

A final challenge facing the ONR UAV/UCAV program is the many competing and better-funded UAV-related thrusts that are starting at the same time: for example, the PEO (CU) VTUAV procurement; the NAVAIR MRE UAV BAA; the DARPA/Navy UCAV-N ATD; and the two relevant Department of the Navy FNCs (time-critical strike and autonomous operations). With the exception of the PEO (CU) and NAVAIR programs, three of these competing activities have substantial ONR 351 participation. The S&T representatives for both FNCs, as well as the individuals responsible for this UAV/UCAV thrust and the UCAV-N ATD, are members of ONR 351. Under these circumstances, particularly as ONR must support the Department of the Navy-mandated FNCs partially out of its existing funding, there will be serious competition for resources, in terms of both money and people, and this small effort could well vanish.

For the Department of the Navy

Dynamics of Naval UAV/UCAV Efforts

In strong contrast to the level of activity in the recent past, the Department of the Navy suddenly finds itself engaged in many UAV/UCAV multiyear projects, with funding ranging from several million dollars per year for ONR 351's proposed UAV/UCAV effort to tens of millions of dollars per year each for the VUAV procurement, the UCAV-N ATD, and the two individual FNCs. Given the success of the Air Force's Predator UAV in Kosovo and the potential capabilities of future UAV/UCAVs, the Department of the Navy's increased interest in the technology is not unreasonable. Unfortunately, however, those programs were all created independently, by different organizations acting in relative isolation and for different reasons, without the benefit of an agreed-on, formal vision for UAVs/UCAVs.

The Navy and Marine Corps need such a plan—a plan with a coherent vision of the future of UAVs. A single, focused naval UAV thrust must be articulated so that these multiple programs can be coordinated and made as complementary as possible to maximize the benefits of the investments. Such a plan does not seem to exist today. The UAV/UCAV thrust under review here could serve as a starting point for the plan.

Program Uncertainties versus "Big" Dollars for UCAVs/Future Naval Capabilities

ONR 351's futuristic UAV/UCAV vision, while admirable, systematic, and technically aggressive, anticipates only modest levels of activity: it is requesting \$2 million to \$4 million per year in UCAV 6.2 funding in the next few fiscal years.

The VTOL UAV and UCAV-N are both near-term programs that address important naval UAV issues of how to permit a UAV/UCAV to operate from a ship, but they pay minimal attention to maximizing the benefits of autonomy. Both, for practical reasons, will inevitably be implemented with today's concepts and technology and are supported by large budgets of tens of millions of dollars per year or more.

The FNC thrusts are intended ". . . to provide critical mass investments . . . leading to transition of key enabling technologies."¹ Twenty percent of the FNC funding is targeted for the 2001-2003 time frame, with the rest aimed further out. As such, the two relevant FNCs, time-critical strike and autonomous operation, seem to complement ONR 351's UAV/UCAV intentions rather well, but both are broader in scope than UAV technology alone; current plans appear to be to fund them very well (\$30 million to \$50 million per year each).

Given the very large imbalance in funding and the competition for resources engendered by the heavy collocation of multiple UAV/FNC responsibility in the ONR 351 organization, there is a real danger that the small grass-roots UAV/UCAV thrust begun last year could simply vanish. Given as well the uniqueness of the ONR 351 long-range vision and systematic approach, and the potential value of what ONR 351 is attempting, it does not seem desirable to simply permit this effort to die. It should, instead, be recognized as a valuable resource and should be coordinated, transformed, and completed, to allow it to serve as the basis for (or at least a major contributor to) the development of an official naval UAV vision of the future and a technology roadmap. The committee believes that the Department of the Navy needs to create a UAV/UCAV master plan that is more comprehensive than the current ESG plan, that includes an S&T component as well as system concepts, and that explicitly acknowledges the existence of UAV/UCAV plans and programs outside the Department of the Navy. Perhaps, as suggested above, the ONR 351 effort could ultimately catalyze an integrated Navy, Marine Corps, Air Force, Army, and DARPA S&T program for UAV/UCAV-enabling technologies.

¹Gaffney, RADM Paul G. II, USN, Director, Test and Evaluation and Technology Requirements. 1999. Future Naval Capabilities Fiscal Guidance—Information Memorandum, Office of the Chief of Naval Operations, N91, The Pentagon, Washington, D.C., November 23.

Assessment of the ONR 351 UAV/UCAV Program

INTRODUCTION

Initiated by ONR 351 in FY99, UAV/UCAV 6.2 activities to date have been devoted entirely to a systematic, top-down S&T planning process (see Figure 2.1) intended to lead logically to a series of roadmaps for future investments in UAV/UCAV-critical technologies. An outstanding team of contractors with recognized experience in UAV-relevant disciplines was assembled, with NRL contributing additional sensor and dynamic networking expertise.

The process began with ONR and the team envisioning the role of UAVs in the battlespace as "... transparent extension[s] of manned combat vehicles [based on multiple] intelligent autonomous air vehicles [operating as a] cooperative and network-centric intelligent system of systems." It was assumed that while a "human dictates the mission at high levels, [software] agents . . . take care of [the] details."¹ This vision is extremely ambitious and proved quite controversial with respect to both the validity of its assumptions and the extent to which it could be said to represent the Department of the Navy's UAV vision of the future.

This initial abstract vision was then transformed, through a series of increasingly detailed studies of missions and vehicle concepts and technology, into a more concrete UAV/UCAV vision that is very far reaching in both its technology and its operational concepts.

First a subset of possible missions for the UAV/UCAV vision was selected and analyzed in some detail by ONR, assisted by two air vehicle prime contractors (Lockheed Martin and Bell). Seven categories of missions that challenged the technical performance of the UAV/UCAVs were addressed:

1. Surveillance and reconnaissance,
2. Lethal air-to-air combat,
3. Lethal air-to-ground combat for the suppression of enemy air defenses,
4. Close air support,
5. Logistics and resupply,
6. Search and rescue, and
7. Mine countermeasures.

¹Allen Moshfegh, Office of Naval Research, "Basic Research Programs on Intelligent Autonomous Agents," briefing presented to the committee, December 13, 1999.

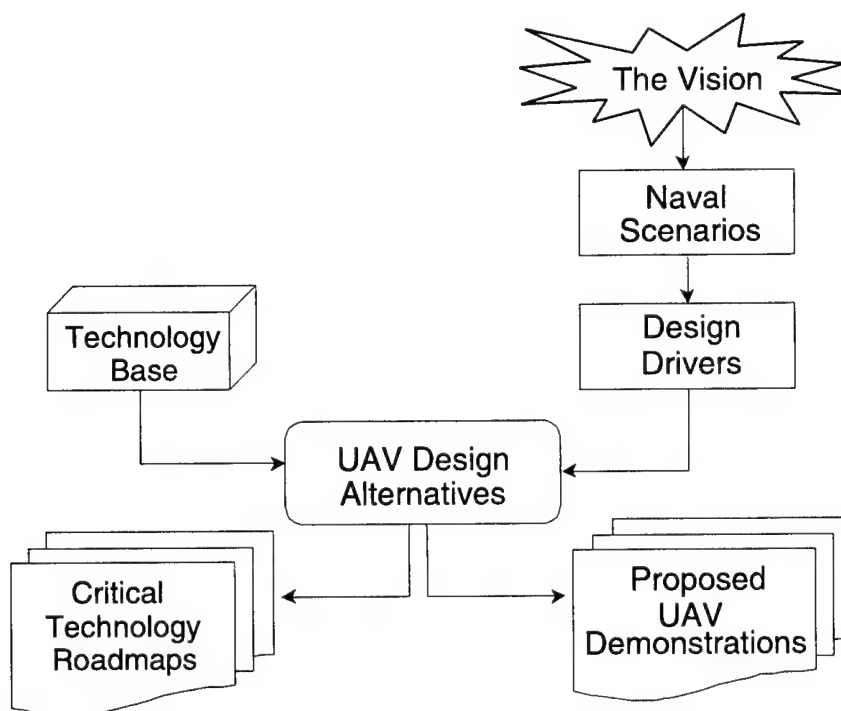


FIGURE 2.1 The ONR 351 UAV/UCAV planning process.

Other missions could (and perhaps should) have been considered, particularly if the vision was intended to be all-encompassing.

From the operational/systems analysis of these missions, performance requirements were established and passed on to all the team members for the identification of critical design drivers. Combining the missions and the design drivers with a knowledge of the existing and expected future technology base, the mission space was divided into three tiers, by mission and by altitude (i.e., high, medium, and low), and a series of conceptual UAV/UCAV design alternatives were created—some fixed-wing and some rotary.

From the design alternatives, the critical technologies needed to implement the vision as it relates to the seven missions were identified and grouped into four technical areas:

1. Vehicle technology,
2. Secure communications and dynamic networking,
3. Sensors and sensor systems, and
4. Autonomy.

The maturity of the existing and projected technology capabilities for each of these was assessed by the contractor and NRL experts. An attempt was made to identify the technological deficiencies that needed additional UAV-specific investments for the UAV/UCAV vision to be realizable in the future and to convert this information into roadmaps that provide descriptions and timetables for future S&T investments aimed at acquiring the missing critical capabilities. Owing to constraints on time and funding, these roadmaps were still rather sketchy at the time of the review.

Finally, an ONR-sponsored workshop² developed a sequence of eight candidate applied research and technology UAV/UCAV demonstrations that addressed critical issues in the following areas:

- Mission planning and execution,
- A robust and reconfigurable dynamic network of networks, and
- Autonomous high-speed, high-precision navigation and control.

No time frame for these demonstrations was given.

The rest of Chapter 2 addresses the committee's impressions, conclusions, and recommendations for the ONR 351 UAV/UCAV program in terms of (1) its vision, (2) the four critical technologies, and (3) the proposed UAV/UCAV demonstrations.

THE ONR VISION

As has been indicated, the Office of Naval Research (specifically, ONR 351) is planning to launch an S&T effort to achieve a UAV/UCAV system that will meet Navy and Marine Corps operational needs in 2020. This system (or network, as it is sometimes referred to) is to comprise high-, medium-, and low-altitude UAVs/UCAVs, both lethal and nonlethal, functioning cooperatively and operating from both ships and shore bases. Although not well conveyed by ONR 351's use of the term "UCAV," the ONR vision in fact embraces the totality of naval UAVs, of which the fighter-like UCAV is but one category.

ONR sees its UAVs/UCAVs as intelligent autonomous vehicles capable of over-the-horizon detection, identification, tracking, and engagement of intelligent adversaries. These vehicles will cooperate and interact to provide a network in the sky to enable a real-time tactical picture and local positioning system for precision target localization and strike and will perhaps even carry out the strikes in some circumstances.³

For autonomy, the long-term vision foresees human guidance as coming only from the highest command level, with intelligent agents taking care of all details—such as takeoff, flying, and landing of the UAV/UCAV, reacting to unexpected events, deciding when a mission is complete, returning to base, and so on—without a continuous significant human-in-the-loop component.

To identify technologies crucial to realizing its UAV/UCAV vision, ONR convoked an S&T roadmap development team made up principally of contractors to flesh out the initial vision. Scenarios for 2020 were developed in which the UCAV system was required to perform missions. The chosen scenarios were all of the high-end nature characteristic of a major theater war, in which U.S. forces faced daunting challenges such as a lack of forward bases, advanced technology systems in the hands of enemy forces, and complete denial-of-satellite-communications capability.

The 12 potential naval UAV/UCAV missions studied included battle management/command, control, communications, computing, intelligence, surveillance, and reconnaissance (BM/C4ISR); electronic combat; suppression of enemy air defense (SEAD); strike; battle damage assessment (BDA); close air support; mine countermeasures (MCM); search rescue; resupply; escort; reconnaissance (RECCE); and combat air patrol (CAP).

The missions sorted naturally into three tiers characterized by the altitude at which the UAV/UCAVs would operate, which led to a partitioning of candidate UAV vehicles into four distinct classes:

- *High-altitude tier (~70,000 ft) (UCAV-H)*—fixed-wing, long-endurance
 - Communication relay and
 - Mobile positioning system for local geopositioning without the Global Positioning System (GPS).

²Held at the Naval Research Laboratory, Washington, D.C., December 1998.

³Allen Moshfegh, Office of Naval Research, "Basic Research Programs on Intelligent Autonomous Agents," briefing presented to the committee, December 13, 1999.

- *Medium-altitude tier (~25,000 ft) (UCAV-M)*—fixed-wing, moderate endurance
 - Targeting,
 - Reconnaissance,
 - Surveillance, and
 - Intelligence gathering.
- *Low-altitude tier (<1,000 ft) (UCAV-L)*—fixed/rotary wing versions, some endurance
 - Precision weapon delivery for strike,
 - Close-in RECCE,
 - Resupply,
 - BDA,
 - Search and rescue, and
 - MCM.
- The CAP mission crosses altitude tiers and so constitutes a fourth class.

This separation into tiers, which leads to different kinds of vehicles and capabilities for each category, seems reasonable. However, if other UAV missions and alternatives—such as the mini- and micro-UAVs under development by DARPA and the Army or a very high dynamics vehicle—are included, the picture might change.

The operational demands derived from a detailed examination of the chosen scenarios were passed to the airframe, vehicle management, sensor, combat, and communication and networking systems developers as conceptual design drivers.

This process of setting forth operational demands yielded highly stressing operational environments, which, when coupled with the assumption of complete intelligent autonomy, often bordered—in the opinion of some committee members—on the implausible. This, in turn, led to requirements for capabilities in intelligent autonomy and robust wireless communications and networking that were judged to be orders of magnitude greater than those available today or envisioned for the foreseeable future.

These requirements represent the critical technology challenges for the future and seem to be appropriate targets for an S&T organization such as ONR. While they may or may not be met in a timely fashion, they certainly will never be met if they are not addressed.

Conclusions and Recommendation

The ONR 351 vision for its UAV/UCAV program is aggressive and very far reaching both in technology and operational concept. For the initiative and creativity shown, the quality of the team, and the excellent effort put into fleshing out the vision through detailed mission analyses, ONR 351 is to be commended. This was definitely an “out of the box” exercise.

While no committee member believed that this vision was not aimed in the right direction, many believed that it suffered from being too ambitious with respect to autonomy. All agreed, however, that the vision was incomplete in a number of significant ways.

Is the Vision Too Ambitious?

The ONR vision pictured swarms of cooperating and totally autonomous UAVs that distribute and share information and assignments and that self-adjust for operational changes, losses, sensor blinding, electronic jamming, and software crashes, all the while still accomplishing their assigned mission without human intervention or active involvement. None of this is remotely possible today. It will take many years of commitment and substantial funding to achieve this vision since there are a number of difficult and fundamental technology problems to be solved. As one example among many, the software systems necessary for autonomous, adaptive, and reliable UAV operations are well beyond the current state of the art, and new methodologies for developing and testing large software systems are clearly essential. These are, indeed, among the real challenges for UAV/UCAV technology of the future and are appropriate targets for S&T investments today.

But, as a practical matter, ONR does itself a disservice by projecting its UAV/UCAV vision, in one leap, directly into the far future, postulating machines with complete, trustable, intelligent autonomy and omitting all discussion of the inevitable nearer-term issues, objectives, and potential of partially autonomous systems having significant human participation. Given that we do not yet know how to implement autonomy we can truly trust, the idea of the battlespace of tomorrow filled with swarms of potentially lethal UAVs zipping around on their own and changing their mind, as it were, on the fly is a scary thought and one guaranteed to put off most warfighters of today.

More important, perhaps, is the fact that those who allocate funding throughout the DOD rarely, if ever, look 20 or more years into the future. They need results today and tomorrow—not decades from now. Presented with a vision for the far future, however rational and probable, most such decision makers will view it as unrealistic or impractical and quickly dismiss it. Funding can be elusive when such views prevail.

To avoid, or minimize, these reactions, ONR *need not* change its long-term vision—although it may want to do so for other reasons—but it does need to complement its current UAV/UCAV vision by describing a reasonable evolutionary process that could take us from here to there, complete with near-term goals that can be considered realistic and practical.

Involving Other Stakeholders and Completing the Vision

ONR's UAV/UCAV effort can hardly thrive in isolation. To be successful it must be linked in a meaningful way to UAV activities elsewhere in the Department of the Navy, particularly to the impending DARPA/Navy UCAV-N ATDs and the FNCs, which are going to get the lion's share of the money. The committee noted that ONR's beginning vision of a UAV/UCAV system and the requirements-generating scenarios appear to have been developed without consulting uniformed planners in the Navy and Marine Corps or other members of the operational community. For this reason, the proposed plan lacks linkage to naval as well as joint near- and mid-term thinking in operational concepts and thus fails to adequately address questions such as the following:

- How will cooperating UAV swarms contribute to theater strategic objectives in the year 2020?
- Why will naval forces need them?
- How will the UAV swarms in a theater interact with other weapon systems?
- How will operational commanders at various levels interact with the swarms?
- How will the advent of UAVs change the requirements levied on the other systems in order to maximize overall force effectiveness and affordability?

A more focused and tractable effort should at least involve Navy and Marine Corps users in jointly defining both a long-term Department of the Navy vision and potential system concepts. In addition, other Department of the Navy organizations need to be involved. N85, for example, describes itself as the "lead spokesman for Navy UAV requirements" and a "resource sponsor for naval UAVs" while simultaneously chairing the Naval UAV ESG.⁴ Clearly, N85 should be a participant in the generation and approval of such a long-range UAV/UCAV vision, but neither it nor any of the acquisition organizations were part of the ONR process. The ONR 351 UAV/UCAV vision is therefore to be considered incomplete insofar as no other Department of the Navy stakeholders were involved in its creation and validation.

Another deficiency relates to the weakness that comes from presenting only the ultimate, totally autonomous far future version of the vision. The way to remedy this weakness would be to add a further level of detail to the vision—another sense in which the vision needs completing.

⁴Col Terry Robling, USMC, Expeditionary Warfare Division, N85, "Department of the Navy Unmanned Aerial Vehicle (UAV) Program: Industrial Day," briefing distributed to the committee by CDR Osa E. Fitch, USN, Naval Air Systems Command, January 18, 2000.

Since the Navy and Marine Corps, and indeed all the military services, are only just beginning to incorporate UAVs into their operational thinking, the reality is that these Services will tend to proceed cautiously with autonomy in general and with the lethal UCAV concept in particular. At first, these vehicles are likely to be teleoperated, with humans in the control loop. For example, Marines on the ground will initially demand that UAVs/UCAVs performing close air support be under direct human control. After confidence has been developed that UAVs/UCAVs can be launched from ships and safely landed on them and operated reliably, the teleoperation mode might progress to the point where humans issue high-level commands that the UAV/UCAV can analyze and execute autonomously. It is only with such a gradual approach that naval commanders will gain enough confidence to permit UAVs/UCAVs to undertake totally autonomous operations. How long this process will take will be a function of the experience gained with current UAVs such as Predator and Global Hawk, the forthcoming PEO (CU) VTUAV system, and the DARPA/USAF/Department of the Navy UCAV ATD.

Therefore, what is also needed for the ONR 351 UAV/UCAV vision is a sequence and timetable for lesser, nearer-term visions that reflects a gradual transition of autonomy from man to machine through appropriate intermediate stages of teleoperation and partial autonomy. Obviously there should be coordination with and a buy-in by Department of the Navy users and acquisition offices on the evolution of UAV autonomy as well as on all other aspects of the vision.

Finally, the vision was judged incomplete in that it did not consider all possible UAV/UCAV missions but confined itself to scenarios requiring relatively high-performance, high-cost UAV/UCAV vehicles. Where, for example, are the inexpensive (and expendable) mini- or micro-UAVs, which should be of interest to the Marines for local information gathering? What about smarter cruise missiles? What other missions could be envisioned if the high dynamic potential of unmanned vehicles can be realized? And so on.

Recommendation

The ONR 351 UAV/UCAV vision appears to have great merit and could be applied beyond the Department of the Navy. At some point in the future, it could serve as a catalyst for an integrated Navy, Marine Corps, Air Force, Army, DARPA, and National Aeronautics and Space Administration (NASA) S&T program focused on UAV/UCAV-enabling technologies. But it is as yet incomplete in many ways. ONR should complete its vision in collaboration with the broader community of Department of the Navy UAV stakeholders, taking into account their (perhaps) more realistic view of the future of intelligent autonomy and also considering a fuller range of potential missions.

CRITICAL TECHNOLOGIES

Of the many technologies needed to realize the UAVs/UCAVs of the future, ONR 351 selected four as being particularly relevant and critical:

1. Vehicle technology,
2. Secure communications and dynamic networking,
3. Sensors and sensor systems, and
4. Autonomy.

Vehicle Technology

Discussions of air vehicle technology were presented by two contractors: fixed-wing configurations were covered by Lockheed Martin Tactical Aircraft Systems and rotary-wing by Bell Helicopter Textron. The briefings were competently handled, as befits the teams' obvious experience and credentials in aircraft technology.

Fixed-wing Vehicles

Fixed-wing candidate vehicles for each of the three tiers were shown—a high-altitude type (UCAV-H), a mid-altitude type (UCAV-M), and a low-altitude type (UCAV-LF)—and their projected performance characteristics were listed. No indication was given of how these designs had been developed, although there was some discussion of on-ship storage issues for the medium- and low-altitude versions. The vehicles proposed looked familiar, as they all seemed to be relatives of existing manned and unmanned designs. This should not be surprising, given that design options are often limited and constrained by current technology projections and that this was a very low budget (~\$150,000) exercise.

While the UCAV-H was intended to be land-based only, both the UCAV-M and the UCAV-LF included ship-compatible VTOL capabilities. As the altitude decreased, the operational ranges and time-on-station capabilities decreased—from 4,500 nautical miles and 24 hours on-station for the UCAV-H to 600 nautical miles and 0.5 hours on-station for the UCAV-LF. At the same time, the speed and maneuverability increased, from a gentle 320+ knots and 1.5 g for the UCAV-H at 70,000 ft to a vigorous 590+ knots and 11 g capability for the UCAV-HF on the deck.

Some of the committee members were interested in the potential of UCAVs to exploit violent maneuvering, i.e., in their very high instantaneous and sustained acceleration g and very high g onset rate capabilities. The ability of unmanned vehicles to generate and take advantage of unsteady aerodynamic, structural, and propulsion interactions in various flight phases could be a distinctive feature in combat lethality and survivability. Unfortunately, while such capabilities are implicit in the 11-g specification given for the hypothetical UCAV-LF, there was no explicit discussion of violent maneuvering capabilities or implementation issues, so the committee was unable to assess the merits of the team's thinking along these lines.

Assuming these design features, critical airframe technologies were then identified and investments were recommended in advanced concepts for reduced weight, specific fuel consumption, and some VTOL propulsion issues. These seemed reasonable as far as they went, but there was no mention of any technologies directly related to violent maneuvering, e.g., unsteady aerodynamics.

Rotary-wing Vehicles

The rotary-wing discussion focused on three low-altitude vehicles (UCAV-LRs). Two of these used a pair of wing-tip-mounted propellers that rotated between horizontal to vertical to provide both helicopter and airplane flight modes; not surprisingly, they bore a strong resemblance to Bell's existing Eagle Eye experimental UAV. The third candidate appeared to be more futuristic: it had separate fixed horizontal and vertical fans but did not seem to possess significant performance advantages. Shipboard storage was discussed, and details of mechanical concepts for the propulsion systems and a variety of trade-off curves were shown. It was obvious that the team understands helicopters. On the other hand, no technology roadmaps were presented, and this was a deficiency.

Concerns and Recommendations

It is the committee's judgment that this aspect of the ONR 351 UAV/UCAV planning exercise is incomplete. The missing roadmaps should be supplied and all the technology roadmaps should elaborate specific program recommendations, so that funding decisions can be based on them.

The impact of low observable (stealth) technology on air-vehicle requirements, designs, and costs was not explicitly addressed in the presentations. Stealth must be considered, as it will be one of the important technology drivers.

The committee also recommends that the violent maneuvering capability be more explicitly considered and included in the long-term vision. The potential for its integration with dynamic automation, networks, and communications to obtain revolutionary long-term system benefits should be evaluated. Major advances in

aerodynamic and other air vehicle technologies (e.g., dynamic lift) have the potential to achieve breakthroughs in maneuvering with concurrent vertical/short takeoff and landing capabilities.

Secure Communications and Dynamic Networking

Advanced UAVs/UCAVs will need to act in concert to achieve mission goals; doing so will require a highly adaptive approach to communications. The networking environment in which a UAV/UCAV ensemble functions will be very dynamic. Opposing forces will attempt to jam communications. There may be limitations on data links for platform control and mission management. Adequate spectrum may not be available, and wideband connectivity in the UCAV network must be affordable. Individual aircraft will be extremely mobile and may well change roles during the course of the mission. The research goal should be to support the most advanced, adaptive, and dynamic form of network-centric warfare. UAV/UCAVs should be capable of pickup team missions in which each aircraft brings whatever capabilities it possesses (e.g., sensors) and makes them accessible to the ensemble as a whole, allowing a coherent picture to emerge even though an individual sensor may be noisy or may have failed.

The dynamic character of this environment requires rethinking many of the details involved in the various layers of the networking infrastructure. The ONR 351 UAV/UCAV program has begun to tackle this assignment. The committee finds the results to be encouraging and on the right track. In particular, the program recognizes that the environment will probably involve high node mobility, limited transmission opportunities, and rapidly changing link characteristics. The UAV/UCAV ensemble will need to rapidly and accurately assess the state of the network; it will also need to efficiently adapt to the actual state and to eliminate the vulnerabilities present in it.

The ONR program has identified five key technology areas on which to focus:

1. Self-organization,
2. Network control,
3. State characterization,
4. Medium access control, and
5. Link quality control.

The approaches being investigated start from the self-organization of both the topology and the grouping of the network nodes; this naturally leads to network control of route, location, and traffic management.

The program has also developed technology matrices mapping the needs onto technology areas and specifying priorities and type of funding (6.1, basic; 6.2, applied; and 6.3, advanced development) for each. Overall, the technology map looks reasonable.

Concerns and Recommendations

Obviously, with the exponential growth in the everyday use of computer and communication networking through local-area networks (LANs), wide-area networks (WANs), cell phones, teleconferencing, virtual work groups, the Internet, and the like, the commercial world is going to be supplying a good deal of the relevant technology. Superficially, the resulting capabilities would seem suited to many UAV/UCAV needs, and if the commercial world becomes interested, the DOD would in general do well to focus on how to apply commercial off-the-shelf (COTS) technology to military needs rather than attempt to develop equivalent capabilities independently.

However, total reliance on COTS would not be wise in this case. While some useful infrastructure will emerge from commercial developments, not nearly enough will be created to support the dynamic network-centric operations that are integral to ONR 351's vision. In the commercial world, people seem to be satisfied with statically assigned resources or, at most, with dynamically assigned resources that tolerate significant setup time (e.g., conference calls). And cellular roaming, which appears to be quite dynamic, actually relies heavily on a fixed infrastructure of physical towers and land lines, implementing only the last step in the connections dynamically. Participants in cooperative UAV swarms, on the other hand, have to be able to pick up whatever signals are

available at the moment and form from them as coherent a picture of the world as possible. There does not appear to be a similar driver for this capability in the commercial world. Thus it seems appropriate for ONR to be addressing the issues of secure communications and dynamic networking directly, as it is doing, while continuing to exploit commercial development whenever possible.

The committee also recommends that in this technology, since so much of the issue is generic to the DOD, not Navy-specific, ONR 351 actively seek alliances with DARPA-ITO and with the other Services.

Sensors and Sensor Systems

Sensors are an obvious part of any UAV system. Current UAVs (e.g., Pioneer, Predator, and Global Hawk) function solely as mobile sensor platforms for generating situational awareness. They have only one role: to get critical sensors into the right places in the battlespace at the right time so that data can be collected and transmitted to human decision makers on some other ground or airborne platform. As simple observers, such situational awareness sensors often have relaxed real-time requirements for information usage. The state of the art of such airborne (often imaging) sensors—e.g., synthetic aperture radar (SAR) and forward-looking infrared (FLIR)—is mature, with many already deployed on both manned and unmanned aircraft and with efforts to enhance performance ongoing throughout the DOD.

Once lethal (i.e., UCAV) missions are added, along with autonomous behavior free from real-time human interaction, additional sensor requirements appear. These requirements are not so much in the physical configuration or measurement capabilities of the individual sensors but in the real-time or near-real-time automatic extraction of useful information from the sensor data. Such data are needed for targeting the weapons and striking or for the autonomous vehicle to exploit as it reacts continuously to its environment. The vehicle's computers must also be able to interpret and optimally combine the information from different sensors on the same platform (i.e., sensor fusion) or, in the case of cooperative swarms of UAV/UCAVs, on different platforms.

The Naval Research Laboratory (NRL) supplied sensor technology expertise for the UAV/UCAV team. It was well informed on the capabilities and maturity of all the relevant sensors and was appreciative of the unique sensor requirements generated by ONR 351's aggressive UAV/UCAV vision.

NRL correctly judged that for most individual UAV/UCAV sensors, the development of physical and measurement capabilities (e.g., size, field of view, sensitivity, and resolution) is generally well in hand. It concluded that for most sensors and sensor applications, "current and future sensor technology meets UAV/UCAV performance requirements," admitting, however, that challenges remain throughout. It should be noted that while this is very likely true for the selected high-end missions addressed so far, it might no longer be true if microvehicles or vehicles with very high dynamics or very low signature are included in ONR 351's UAV/UCAV vision. The requirement for very small size offers significant challenges to the physical configuration and performance capabilities of individual sensors, while that for very high dynamics and/or stealth puts restrictions on external sensor apertures, which may call for conformal microwave and optical phased array technology capabilities not yet developed or envisioned.

Although the physical aspects of sensor technology can probably be expected to develop fast enough to meet the identified UAV/UCAV needs without special attention from the UAV community, the additional requirements for automatic information extraction and sensor fusion may not. Thus, special investments will be needed in cooperative multiplatform sensor fusion and automatic target recognition (ATR). Both of these are difficult problems yet critical to the success of ONR's vision. For example, despite more than 25 years of substantial investment in R&D, ATR capabilities remain limited at best, working successfully only against selected, unobscured targets in the open. As yet, camouflage easily defeats most ATR algorithms. How humans so easily accomplish such tasks is still not understood. It may well take another quarter century or more before ATR begins to offer the capabilities needed for truly reliable, autonomous operation of UAVs. Just because the task is difficult, however, does not mean it should not be addressed today.

The committee agrees that cooperative multiplatform sensor fusion and ATR are probably the two most significant challenges to ONR 351's UAV/UCAV vision in the area of sensors. Other significant sensor deficiencies noted include the need for good collision-avoidance sensors (which also may call for UAV-unique invest-

ments) and the inability of existing sensors to reliably detect minefields and chemical and biological agents at a distance.

Concerns and Recommendations

Like the roadmaps for other critical technologies, the roadmaps produced for sensors are superficial at best, with broad topics assigned to coarse 5-year intervals. The work is unfinished. To be useful, the roadmaps must contain details such as near-term program options.

Other sensor issues will certainly arise if the guiding vision is extended to include very small (e.g., mini- and microplatforms) or very-high-dynamic vehicles. These will have to be addressed at that time. The committee believes that the ONR UAV/UCAV program should focus on automatic information extraction for ATR, as well as on cooperative multiplatform sensor fusion. ONR should track and exploit the cutting-edge work in this area, such as that of the DARPA Moving and Stationary Target Acquisition and Recognition (MSTAR) program.

Another concern is that while the sensor roadmap contains an excellent review of related technologies and efforts under way in the Navy S&T community, it is purely "Navy" in character and emphasis and does not represent a joint vision of work contributed by other agencies or Services. The committee believes that focus must be expanded to acknowledge the standards, equipment, sensors, and software tools provided by the DOD's distributed common ground systems (DCGSs), DARPA, the Air Force, and the Army. By doing so, the Department of the Navy could capture the investment made by other agencies and Services, thereby lessening the investment required to achieve UAV/UCAV-level capability.

Autonomy

Autonomy was a featured subject throughout the review. It formed the centerpiece and the most controversial element of ONR 351's overall UAV/UCAV vision of the future. It was discussed competently and at some length by both airframe contractors (Lockheed and Bell) in the context of air vehicle management and avionics, and its technology issues were examined by the Draper Laboratory.

ONR 351 presented an ambitious view of intelligent autonomy in the context of its UAV/UCAV vision of the future. Explicit in the vision is the requirement that the UAV/UCAV must be able to "function without a continuous significant human-in-the-loop component," to "perform coordinated group missions," and to "take [real-time] advantage of opportunities and manage contingencies."⁵ As there are no software systems that can perform these functions today, achieving the projected level of autonomy may be the most challenging of the four critical technologies.

After ONR 351's systematic (mission → requirements → technology) process had been discussed, the extraction of autonomy-related requirements from the many missions considered was discussed. No attempt was made to present a complete list of derived requirements. Instead, a few examples were given to illustrate the process.

Finally, the candidate technologies deemed necessary to meet the derived autonomy requirements were identified and divided into two broad categories, each encompassing a wide range of somewhat eclectic topics:

- Situation awareness
 - Three-dimensional mapping,
 - Sensor and data fusion,
 - Natural language processing,
 - Adaptation and learning,
 - Image understanding, and
 - Human-machine cooperation.

⁵Allen Moshfegh, Office of Naval Research, "Basic Research Programs on Intelligent Autonomous Agents," briefing presented to the committee, December 13, 1999.

- Planning and decision making under uncertainty
 - Behavior-based intelligence,
 - Path planning,
 - Multientity control,
 - Self-organizing systems,
 - Planning and control architectures,
 - Metaheuristics,
 - Mathematical programming, and
 - Hierarchical decomposition.

ONR 351 considered each of these technologies in terms of its relevance or applicability to the long-term vision and in terms of its maturity, as measured by the class of funding needed (6.1, 6.2, or 6.3). It identified seven critical technologies for immediate attention. For situation awareness there were four: sensor and data fusion, adaptation and learning, image understanding, and human-machine cooperation. For planning and decision-making under uncertainty there were three more: multientity control, planning and control architectures, and metaheuristics. The committee agrees that all of these topics are important but recommends explicit UAV/UCAV investments be considered for only a few of them, as discussed below.

Concerns and Recommendations

Autonomous systems are emerging as a very important national interest that reaches across many current and planned combat and support systems within the Services. Unmanned combat systems have the potential to reduce the risk of losing personnel and to reduce the cost of ownership for many military missions. High levels of autonomy are desirable in unmanned combat systems because lethality and survivability can be improved with much less communications bandwidth than would be needed by preprogrammed or remotely operated unmanned systems.

Despite the very considerable potential benefits of unmanned autonomous systems, total autonomy is not necessarily an appropriate goal for a combat system. The battle commander must have sufficient command and control of his assets to accomplish the fundamental processes of synchronized movement, focus of firepower, and distribution of firepower for his forces. The benefits of high levels of autonomy for unmanned systems can be realized only if there are corresponding levels of command and control to ensure that the unmanned assets are coordinated with other battlefield forces.

Levels of Autonomy

The presentations by the ONR team spoke of intelligent autonomy but did not explicitly define it. It is useful to understand the full range of possibilities. One possible classification for levels of autonomy is presented in Table 2.1. This classification is intended to be a fairly coarse, one-dimensional mapping of what is arguably a multidimensional space.

Other classifications of autonomy are provided by Sheridan⁶ and by Parasuraman.⁷ Using the classification system in Table 2.1, most combat aviation automation exhibits level 2 autonomy. It is highly unlikely that the

⁶Sheridan, Thomas B., 1982, "Supervisory Control: Theory and Experiment for Application to Human Computer Interaction in Undersea Remote Systems," MIT Man-Machine Systems Laboratory Report, Massachusetts Institute of Technology, Cambridge, Mass.; 1984, "Supervisory Control of Remote Manipulators, Vehicle and Dynamic Processes," *Advances in Man-Machine Systems Research*, W.B. Rouse (ed.), JAI Press, a subsidiary of Elsevier Science, Greenwich, Conn. (Canadian National).

⁷Parasuraman, R., 1987, "Human Computer Monitoring," *Human Factors* 29:695-706; Parasuraman, R., T. Bahri, R. Molloy, and I.L. Singh, 1991, "Effects of Shifts in the Level of Automation on Operator Performance," Proceedings of the International Symposium on Aviation Psychology (6th Conference, Columbus, Ohio).

TABLE 2.1 One Possible Classification Scheme for Levels of Autonomy

Level	Name	Description
0	Human operated	All activity within the system is the direct result of human-initiated control inputs. The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
1	Human assisted	The system can perform activity in parallel with human input, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input. An example is automobile automatic transmission and anti-skid brakes.
2	Human delegated	The system can perform limited control activity on a delegated basis. This level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
3	Human supervised	The system can perform a wide variety of activities given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviors that are not within the scope of its current directed tasks.
4	Mixed initiative	Both the human and the system can initiate behaviors based on sensed data. The system can coordinate its behavior with the human's behaviors both explicitly and implicitly. The human can understand the behaviors of the system in the same way that he understands his own behaviors. A variety of means are provided to regulate the authority of the system with respect to human operators.
5	Fully autonomous	The system requires no human intervention to perform any of its designed activities across all planned ranges of environmental conditions.

UAV/UCAV system could depend on level 2 or lower autonomy. The difficulty in communicating with the vehicles, particularly under combat conditions, suggests that level 3 or level 4 autonomy would be required.

ONR 351's UAV/UCAV vision implies that level 5 (fully autonomous) is the ultimate target, but the committee seriously questions this approach. The committee believes that level 5 autonomy for UAVs/UCAVs may not be desirable on the battlefield, regardless of its technical or economic advantages. Combat systems need to be under the supervision of the joint task force/theater commanders to behave as a coordinated force. As a result, the pursuit of level 5 autonomy is not recommended for the UAV/UCAV, although it might be appropriate for some isolated systems that do not participate in an integrated force structure.

Technical Issues in Pursuit of Level 3/4 Autonomy

There are very few technology issues unique to the Navy in the pursuit of level 3 or level 4 autonomy. However, the pursuit of these levels of autonomy is important to the nation, so it would be appropriate for the Navy to pursue them and of benefit to all of the Services. The autonomous operations FNC is an important thrust within the Navy Department for both cost and operational capability reasons.

A review of the autonomy items proposed under the ONR UAV/UCAV 6.2 program indicates that many of the issues are more mature than the issues that 6.2 funding should address. Table 2.2 provides a detailed commentary by the committee on the ONR 351 proposed topics. *Italics indicate the committee's recommended 6.2 research areas for the ONR 351 UAV/UCAV program.*

TABLE 2.2 Summary Evaluation of ONR's Proposed Autonomy Topics

Topic ^a	Maturity	Comment
Three-dimensional mapping	>6.3	Fielded systems are available that can create and manipulate three-dimensional representations of objects in real time. This topic is peripheral to level 3 or 4 autonomy.
Sensor and data fusion	6.1/6.2/6.3	An abundance of effort is under way in this challenging area yet basic issues remain unresolved. UAV/UCAV demonstrations of sensor and data fusion are warranted.
Natural language processing	6.1/6.2/6.3	Commercial systems are functioning today yet basic issues remain unresolved. The grounds for this capability are very weakly based on existing air traffic control system limitations.
Adaptation and learning	6.2	This is an important area that would benefit from 6.2 research. However, the behaviors of combat systems should be directly managed as validated knowledge. Not recommended for UAV/UCAV efforts.
<i>Image understanding</i>	6.2	This is an important research area that would benefit from 6.2 effort. The importance of image understanding is based on assumptions about the use of imaging sensors, such as SAR and FLIR. This topic is relevant to ONR UAV/UCAV and recommended for inclusion in 6.2 funding.
<i>Human-machine cooperation</i>	6.2/6.3	While progress in this area has occurred and some capabilities are more advanced than 6.2 funding would imply, there are many issues that have not been addressed in control of unmanned systems. Recommended for ONR UCAV at 6.2 and 6.3.
Behavior-based intelligence	6.3	Another name for level 2 autonomy. Demonstrations in a UCAV mission context are recommended.
Path planning	>6.3	This is a mature technology. Demonstrations are warranted as a part of ONR UCAV, but funded development activities are not.
<i>Multientity control</i>	6.2/6.3	Some value may result from 6.2 funding, but most emphasis should be on 6.3 demonstrations in the UCAV mission context.
Self-organizing systems	6.1/6.2	While this is valuable as a research topic, it does not seem critical to the ONR 351 program.
Planning and control architectures	>6.3	This is a heavily developed area, with many alternatives that could be demonstrated in a UCAV mission context.
<i>Metaheuristics^b</i>	6.2/6.3	Some benefit may result from 6.2 funding, but most of the emphasis should be on 6.3 demonstrations in the UCAV mission context.
Mathematical programming	>6.3	A heavily explored area of marginal relevance to UCAV. Not critical to UCAV.
Hierarchical decomposition	>6.3	Relevant to UCAV, but heavily explored and mature technology. Does not require ONR UCAV 6.2 funding.

^aItalics indicate the committee's recommended 6.2 research areas for the ONR 351 UAV/UCAV program.

^bMetaheuristics combines techniques such as genetic algorithms, simulated annealing, tabu search, fuzzy systems, neural nets, and other hybrid heuristics.

It is not evident from this eclectic list which underlying mathematical and engineering principles unify these topics. To date, autonomous system design appears to be based largely on heuristic rather than structured approaches, and this apparent weakness deserves research attention. The committee believes that the state of the art for some of these autonomy topics is more advanced than represented by the ONR 351 UAV/UCAV analyses. As a result, some effort should be directed to demonstrating the existing technology base in a naval UAV/UCAV context. The demonstration program will leverage the best efforts under way and may reveal shortfalls in technology better than the paper analyses; it may also avoid unnecessary investment in mature technology areas. In general, it is more prudent to demonstrate that gaps in technology exist rather than to simply assume that they exist.

Over the past 18 months, commercial software systems have begun to emphasize autonomous operations in a wide variety of settings. Often labeled “software agent” technology, flexible and autonomous software systems for medical operations, e-commerce, logistics, and manufacturing are rapidly emerging. These systems herald a major shift in information architecture, from centralized (client-server) systems to distributed collaborative computing systems on a large scale. This shift is enabled by the communications infrastructure of the Internet, which allows widely distributed computing resources to collaborate in the performance of enterprise-wide activities.

This emerging trend in commercial software has strong implications for the Navy Department’s planned efforts in autonomous systems. Rather than attempt to lead the development of science and technology for all aspects of autonomy, it would be wiser for the Department of the Navy to leverage many of the current commercial software efforts in this area. This would permit S&T funding to focus on a relatively small set of Navy-unique issues at the 6.1/6.2 level, using 6.3 resources to apply the emerging commercially developed technologies to prototype naval platforms and missions.

Commercial software relevant to the command and control of distributed autonomous systems—but not unmanned systems—is being developed at a rapid pace. The most fertile area is in business intelligence and business operations software. One example is supply chain management and logistics. Several commercial software vendors now provide frameworks for collaboration and cooperation between companies. These frameworks provide representations of strategic and tactical interests of the collaborators and provide for information distribution and the synchronization/fusion of data and plans. Some of these systems also interface to real-time process control systems that have dynamics not too dissimilar to flight vehicles.

None of the business-oriented commercial software frameworks will be applicable to the autonomous operations FNC without incentive. A strong 6.3 demonstration program that funds interface development and shows existing frameworks in Navy UAV/UCAV mission contexts could showcase these emerging software packages. By investing in the creation of a broad opportunity to demonstrate existing technology rather than in narrowly funded and possibly redundant 6.2 exploratory work, the Navy Department could make much faster progress toward autonomous operations. This should not be taken to mean that investment in autonomy is not required, but that a larger share of the investment should be directed toward demonstration rather than exploration.

Not all of the Department of the Navy’s needs will be met by commercial software development, so investment in 6.2 (exploratory development) is warranted in the areas italicized in Table 2.2. Careful coordination with other research programs at ONR and the other Services is recommended so as to gain the most benefit from the 6.2 funding.

The committee also believes that ONR should consider conducting an active outreach program using 6.2 funding to leverage emerging commercial software technology for autonomy. The objective of this outreach should be to encourage the growth and recognition of a focused autonomy community that facilitates communication and joint development across industry, government, and academia. Professional societies, special interest groups, and regular Department of the Navy-sponsored conferences and symposia could provide a forum for this community.

While the basic technology for autonomous operations is evolving at a rapid pace under commercial pressures, it is very unlikely that commercial software developers will share their successful design and development methods with other companies or the Navy Department. They will consider their successful methods for requirements capture, knowledge development, integration, and test and evaluation to be highly proprietary and of great

commercial value. As a result, the committee believes that the Services will need to invest in methods for characterizing autonomy requirements and for designing to meet these requirements, including test and evaluation methods. Government funding of the effort to identify and describe best practices for autonomy design would give the public access to techniques that they could not obtain commercially.

The committee recommends that ONR should involve itself in specific funded S&T efforts aimed at identifying and publishing best practices for the design, development, and evaluation of complex autonomous military systems.

PROPOSED UAV/UCAV DEMONSTRATIONS

Participants in an ONR-sponsored workshop developed a sequence of eight candidates for applied research and technology UAV/UCAV demonstrations:

- Mission planning and execution
 - Autonomous, real-time mission/path replanning, obstacle avoidance, and resource allocation;
 - Autonomous and cooperative target cueing and ATR;
 - Takeoff and landing on an air-capable ship in high seas using passive sensors for navigation; and
 - Autonomous in-flight refueling.
- Robust and reconfigurable dynamic network of networks
 - Dynamic Internet-in-the-skies (connectivity and real-time sharing of information) and
 - Mobile positioning systems: jam-resistant, precision geolocation system.
- Autonomous high-speed, high-precision navigation and control
 - Low altitude in-clutter navigation using passive sensors and
 - Autonomous tracking of an intelligent adversary.

The sequence of the demonstrations was intended to confirm the evolution of UAV/UCAV capabilities such that each successive demonstration builds on its predecessor. There was no indication of the time frame for these demonstrations or how they might relate to near-term UAV/UCAV 6.2 efforts.

One of the hardware platforms Draper Laboratory could make available for these demonstrations is a very interesting small UAV helicopter already capable of modest autonomy in flight control—it can stabilize itself in wind. Several of the proposed demonstrations would use this UAV and hence could be done quickly.

Concerns and Recommendations

While this selection of candidates for demonstration appears to have been a creative exercise, given the uncertainties and incompleteness of the UAV/UCAV thrust, the committee believes it to have been premature. The candidates for demonstration are certainly representative of the kinds of activities that should take place, but they should not be elaborated any further at the present time. In particular, they might well exceed 6.2-level funding and would have to be coordinated with the other Department of the Navy and DOD stakeholders in UAV.

SUMMARY RECOMMENDATIONS

With respect to the ONR 351 UAV/UCAV program, the committee recommends that ONR should do as follows:

- *Strive to become fully integrated* within the Department of the Navy UAV/FNC community. The relevant programs—the ONR 351 UAV/UCAV program, the DARPA/Navy UCAV-N, the PEO (CU) VTUAV procurement, the NAVAIR MRE UAV BAA, and the Department of the Navy FNCs—are now largely independent. They should be coordinated according to an agreed-on focus. The Navy should also take advantage of the wide range of results obtained by other Services.

- *Complete the vision* and make it more realistic by recognizing the limited applicability of total (i.e., level 5) autonomy, adding an outline of and a timetable for human-machine partnerships through a series of intermediate visions. The mathematical and engineering sciences on which autonomous system design and evaluation will be based should be developed.
- *Engage other appropriate Department of the Navy UAV stakeholders* and reexamine their missions to ensure that the UAV/UCAV vision responds to the needs of the whole naval community.
- *Complete the technology roadmaps* after this reexamination.

For the critical technologies the committee recommends as follows:

- *Vehicle technology* will evolve without being given special emphasis by an ONR S&T program. Accordingly, ONR should plan to invest only in R&D pertaining to (1) missions that are unique to the Navy, such as landing on a ship and ASW-related operations and support, and (2) overall affordability.
- For *communications and networking*, the commercial sector will not address all the issues. ONR should focus on secure communications and dynamic networking directly, as it is doing, while continuing to exploit commercial development whenever possible.
- *Sensors and sensor systems* hardware will evolve without special attention from an ONR S&T program. ONR should focus on software and algorithms for information extraction and fusion rather than on hardware issues. A much-better-focused program of enabling technology development and demonstration than seems to have been put in place so far is essential if limited funds are to produce significant results.
- For *autonomy*, the commercial sector will not address all of the Navy's needs. ONR 6.1/6.2 investments are warranted in several important areas—image understanding, human-machine interaction, multientity control, and metaheuristics—as well as in a systematic examination of the scientific and engineering principles upon which autonomous operations are based. Careful coordination with other R&D programs of the Navy and the other Services is recommended. ONR should leverage commercial software to emphasize naval-unique applications, demonstrations, and exercises, and it should encourage the formation of a community focused on autonomy that facilitates communication and joint development across industry, government, and academia by means of Navy-sponsored symposia and the like. Finally, the committee recommends that ONR should specifically fund S&T efforts aimed at identifying *and publishing* best practices for the design, development, and evaluation of complex affordable autonomous military systems.

Integration with Other Related Department of the Navy and Department of Defense Efforts

INTRODUCTION

The committee was given information on relevant Department of the Navy and Department of Defense (DOD) unmanned aerial vehicles (UAVs) and uninhabited combat air vehicles (UCAVs) programs so that it could assess the ONR UAV/UCAV program with respect to its relevance for meeting naval priorities, its cost and time scale, duplication of effort, and scientific and technical quality. Figure 3.1 compares the UAV and UCAV programs presented to the committee.

PROGRAM ISSUES

The Department of Defense's history of UAV technology has been long, complex, and often frustrating to those advocating rapid development. The United States had early success with remotely piloted vehicles (RPVs) in the form of remotely controlled aircraft for radiation monitoring during the South Pacific atomic bomb tests in the 1950s and modified target drones (AQM-34, Buffalo Hunter) for high-altitude photoreconnaissance over North Vietnam in the 1960s. But even after Israel's successful demonstrations in the 1973 Yom Kippur War, the U.S. military exhibited little interest in tactical UAVs (TUAVs), and it took literally decades for enthusiasm to build.

The 1980s saw the beginnings of interest as both the Army and the Navy attempted to develop and field a TUAV. The Army's Aquila program, plagued by creeping requirements and lacking a strong sponsor, spent about \$1 billion before it was finally cancelled in 1988, making many decision makers wary of UAVs. However, the 1980s produced one notable UAV success—the Navy's Pioneer. Military operations in Libya, Lebanon, and Grenada had shown the need for an inexpensive over-the-horizon reconnaissance and targeting capability. In response, the Navy, in 1985 and 1986, quickly acquired and deployed the Pioneer through a fly-off competition between contractor-funded candidates. In Operation Desert Storm, the Pioneer's documented success in supporting combat operations and providing timely battlefield intelligence at last gave the United States its own clear proof of the battlefield potential of TUAVs.

And so in the 1990s, UAV developments began to accelerate. There was still little overall coordination by the DOD, and the Army, Navy/Marine Corps, Air Force, and DARPA pursued (with few exceptions) independent development paths. Most of these UAV thrusts arose bottom-up from the enthusiasm of individuals or organizations rather than top-down from a recognition by the Services or the DOD of the value and potential of UAVs and the need for them.

Army UAV Programs

After first deploying the Pioneer jointly with the Navy, the Army opted to develop its own low-altitude reconnaissance TUAV, the Hunter. Initiated in 1989, the program advanced to the point of selecting a single contractor in 1992, with low-rate initial production (LRIP) in 1993. Yet by 1997, production was stopped as the projected requirements of future systems seemed to be quickly outrunning the Hunter's capabilities. Nevertheless the existing Hunters were deployed in 1999 in Kosovo, where they performed well.

After participating in a joint Army/Navy advanced concept technology demonstration (ACTD) with the Outrider TUAV, the Army again began to develop another low-cost TUAV, culminating in a fly-off competition between four candidates, including the Outrider. In December 1999, the Shadow-200 TUAV was selected and an engineering and manufacturing design (EMD)/LRIP contract for four systems awarded. Each system includes three air vehicles and the associated ground control, launching, and logistic elements. Testing and evaluation (T&E) are scheduled for the third quarter FY01.

Air Force UAV Programs

The Air Force's Predator, a medium-altitude endurance (MAE) UAV with electro-optical (EO)/infrared (IR) and synthetic aperture radar (SAR) sensors was developed in the mid-1990s as an ACTD managed by the Defense Airborne Reconnaissance Office (DARO) and eventually assigned to the Air Force by the Pentagon. Built in large numbers (~50 so far), the Predator was deployed to Europe several times in the second half of the 1990s and became the best-known and best-performing UAV in the air campaign in Kosovo. The Predator can be expected to remain in service many years as lost vehicles are replaced and performance enhancements applied.

In addition to the Predator, the Air Force also has several large and ambitious UAV activities under way with DARPA: the Global Hawk high-altitude endurance (HAE) UAV, which grew out of another DARPA/DARO ACTD of the mid-1990s, and a more recent UCAV ATD program.

Intended to demonstrate "the technical feasibility for a UCAV to effectively and affordably prosecute 21st century SEAD/strike missions . . .,"¹ the UCAV program began in 1998 with multiple contractor study phase and is now well into detailed design and fabrication by a single contractor. First flights are scheduled for FY02 and are intended to demonstrate "human-in-the-loop detection, identification, location, real-time targeting, weapons authorization, weapons delivery and target damage indication." Multivehicle coordination in flight is envisioned for the later demonstrations.

Navy UAV Programs

During much of the 1990s the Navy seemed content with the Pioneer. However, toward the end of the decade a more focused UAV effort developed. Responsibility for determining and addressing requirements for the Navy UAV program as a single Navy point of contact and for directing programming and budgeting for all Naval UAV programs was assigned to the Aviation Systems (N854) organization of the Chief of Naval Operation's Expeditionary Warfare Division (N85).

The situation evolved rapidly in the last 2 years. The following description and comments pertain to the situation at the time of this writing. In 1998, the Naval UAV Executive Steering Group (ESG) was created to "provide a forum for coordination of Navy/Marine Corps UAV issues, [to] develop and validate the Naval UAV roadmap and [to] speak with one voice for Naval UAV issues."² Chaired by N85, the ESG has representation from a wide range of Navy and Marine organizations, including the Surface Warfare Division (N86), the Air Warfare Division (N88), the Program Executive Office for Cruise Missiles and UAVs (PEO CU), the Marine Corps Combat Development Command (MCCDC), NAVAIR, NAVSEA, and SPAWAR.

¹Lt Col M. Leahy, USAF, "DARPA/USAF UCAV ATD," briefing to the committee, October 12, 1999.

²MajGen Dennis Krupp, USMC, Director of Expeditionary Warfare, N85, "Naval UAV Executive Steering Group," briefing to the committee, October 16, 1999.

The ESG has created a Navy UAV roadmap that envisions the Pioneer being replaced in FY03 to FY05 by a vertical takeoff and landing tactical uninhabited aerial vehicle (VTUAV), to be developed; a Navy MAE or medium-range UAV, to be fielded in FY06 to FY14; and a Navy UCAV, to be fielded in the more distant future (FY15 to FY25). Mini/expendable and micro-UAVs were also postulated for the out years from FY06 on. In the near and medium-term future, rather than competing with the Air Force for organic HAE (Global Hawk) and MAE (Predator) capabilities, the plan reasonably proposes achieving interoperability with these systems via the Tactical Control System (TCS), which comprises the software, software-related hardware, and ground-support hardware necessary for the control of Predator and other advanced UAVs (e.g., UCAVs) and which also ensures receiving and disseminating real-time UAV imagery and data (e.g., from Predator and Global Hawk).³

Following this plan, the PEO (CU), after a fly-off of competing designs, awarded a contract in February 2000 for the engineering and manufacturing development of the helicopter-like VTUAV. In addition, NAVAIR recently issued a broad agency announcement (BAA) for a study of an advanced multirole endurance (MRE) UAV that will provide reconnaissance, surveillance, targeting, and attack (RSTA) and communication relay capabilities and that will be capable of both austere land-based and sea-based operation. Thus, two major Department of the Navy UAV thrusts have just begun in response to the ESG's UAV plan.

In retrospect, the ESG plan, while broad in scope, seems to be weak in terms of requirements leadership and may not be as ambitious as it could have been, for events have overrun it. Toward the end of 1999, DARPA approached the Navy, going not through N85 and the ESG but directly to the CNO, and proposed a joint DARPA/Navy version of the existing DARPA/USAF UCAV ATD; the proposal was accepted. It may be recalled that UAVs were on the ESG's long-range plan, but for the far future, with fielding projected after FY15.

Now called UCAV-N, this nascent ATD seeks to leverage the existing DARPA/USAF UCAV effort and technology with an infusion of DARPA funds and to focus on Navy-unique issues such as shipboard operation and ship design, mission control integration with existing naval systems, naval concepts of operations (CONOPS) for the suppression of enemy air defense (SEAD), strike and surveillance, and affordable operations and support (O&S). Phase 1 studies and analysis with multiple contractors will begin this year.

NAVAIR and the ESG have little choice but to absorb this UCAV program and adjust the roadmap and perhaps some near-term plans. In addition, the Office of the Chief of Naval Operations Air Warfare Division (N88), already a member of the executive committee of the ESG, will be taking on a larger role in UCAV. The DARPA initiative has managed to inject a good deal of excitement and some accompanying confusion (at least for the time being) into the Navy UAV community. The UCAV-N program will have a big impact on the Navy's future UAV programs, providing a strong and well-funded focus for advanced concepts.

Simultaneously and quite independently of the UAV community, the Department of the Navy decided to restructure its S&T programs into 12 future naval capability (FNC) "spikes" to enhance the effectiveness of its S&T efforts by providing critical mass funding to selected technologies deemed critical to the future of the Navy Department. At least 5 of the 12 FNCs bear on UAV missions and technology, with the two most relevant—time-critical strikes and autonomous operations—coincidentally operating out of the ONR 351 organization.

The ONR 351 UAV/UCAV Program

It is into this traffic-filled environment that the ONR 351 (6.2) S&T program is being launched. In creating its ambitious UAV/UCAV vision and the associated critical technology roadmaps, ONR 351 has so far not coordinated its activities with the other Navy Department and DOD participants in the UAV/UCAV arena. This is a dangerous approach when there is competition for resources and funding, and it must be corrected. On the other hand, independence is not entirely without merit, for ONR 351's extraordinary vision addresses head-on several issues that have been underplayed, unaddressed, or unappreciated by the other programs (requirements

³The committee did not review the Army's Tactical Exploitation System (TES) or the USAF's deployed transit system (DTS), which are also relevant to UAV/UCAV objectives. These efforts already contain level 4 capability and are along a path that integrates all sensor data.

leadership) and that may have been difficult to evolve in the context of the much nearer term projects. These issues include the following: the role, potential, and manifestations of autonomy technology in future UAV systems; the many communication/networking and sensor fusion issues arising from the UAV-to-UAV cooperative behavior that is inherent in the full realization of network-centric concepts; and, finally, the laudable attempt to create UAV/UCAV technology roadmaps to guide the S&T investments. While all the UAV/UCAV programs and plans address technology from the point of view of its existence and maturity, none try to plan for driving the technology in the right direction, as was the goal of ONR 351's effort.

Even the current OSD UAV Master Plan, which attempts to coordinate all Department of Defense UAV activities, fails in this respect by addressing primarily budgets and development/deployment schedules. The committee believes that a DOD-wide S&T roadmap for UAVs would be extremely useful for all the Services.

The Department of Defense technology development approach (TDA) is an existing process that the Navy could use to ensure that ONR S&T programs are planned and executed in coordination with other Navy agencies, other Services, and other leading industry, government, and university participants.

One of the key TDAs that relates to UAV/UCAV is the Department of Defense fixed-wing vehicle (FWV) TDA. Other TDA areas, such as integrated high-performance turbine engine technology (IHPTET), avionics (which covers architecture; radio frequency (RF) and electro-optical (EO) sensors, signals, and data processing; and information management), and rotary wing (RW), to name just a few, are also relevant to UCAVs.

The TDA calls for an integrated plan and agreed-to partitioning of work among the Services, industry, and NASA. All participants are part of the planning process and are required to commit themselves to achieving results in their portion of the work. Furthermore, TDA plans and programs include descriptions of key payoffs (to the warfighter), goals (at the system level), and objectives (for the technology developers).

The payoffs, goals, and objectives are quantified and measured periodically. Goals, such as doubling engine thrust-to-weight ratios over a given number of years (for IHPTET), and the specific technology objectives that correspond to those goals are critical for connecting the S&T developers to operational benefits and ensuring on-time delivery of mature technologies.

From many points of view the ONR 351 program is highly complementary to the rest of the Navy's UAV activities and clearly should be integrated with them and coordinated and exploited by them, albeit somewhat after the fact. Unfortunately, in view of its projected small size (only a few million dollars in 6.2 funds per year), it may very well be simply eaten up in the struggle for resources.

Research and Development Funding

The coordination difficulties facing the ONR 351 UAV/UCAV program are not unique. A general lack of alignment between ONR S&T investment plans and the operational needs of the Navy has impelled the Navy to initiate the FNCs process. The core of the problem is that the budget authority flow-down process at ONR creates stovepipes⁴ of interest. To some, this amounts to investing seed money to accelerate research in areas of interest. To others, the investment plans appear unrelated to the Navy's needs. The FNC process will realign a significant portion of the Navy's S&T budget to the areas of greatest interest to the Navy. The committee expects that it will cause increased amounts of ONR budget to be shifted to FNCs and that eventually the S&T planning and budgeting process will be overhauled.

It is important to remember that the goals of 6.1 and 6.2 research are to look out for the needs of the "program after next." The basic research community should not be overly taxed to support UAV/UCAV development programs; it should, however, be aware of what is going on, the capabilities being developed, the lessons learned, and the remaining challenges. When there is a problem with the near-term programs that the community alone can solve, it should do so. However, its main goal is to postulate an exciting future and then to work on the technical

⁴The term "stovepipe" refers to a program that stands alone, i.e., is constructed and supported to work by itself.

enablers to make that future possible. The basic research community must be granted considerable leeway in imagining the future: the details are cloudy and even major assumptions will need revision over time. However, the main technical foci will tend to be independent of the particular assumptions that are made. Whether or not the Global Positioning System (GPS) will be jammable, for example, does not affect the overall assessment that an ensemble of UAVs/UCAVs will need a high degree of autonomy, self-organization, and adaptivity.

There are three areas in applied research that need coordination by ONR. The first is duplication and prioritization with the projects and demonstrations in the FNCs. Six of the twelve FNCs may overlap with the ONR 351 UAV/UCAV program: autonomous operations, time-critical strike, information distribution, littoral ASW, and organic mine countermeasures.

The second area needing coordination is ONR 351 alignment with the UCAV-N program. This will be primarily a matter of synchronizing with the DARPA/USAF UCAV technology database and phasing the Navy's S&T accordingly.

The third area needing coordination is alignment with N85, the Naval UAV ESG, and the several current UAV-related thrusts of the Department of the Navy—for example, the PEO (CU) VTUAV procurement and the NAVAIR MRE UAV BAA—and their requirements for technology refreshment and an expansion of mission and capabilities.

TECHNOLOGY ISSUES

Overriding Concerns

In addition to the program issues discussed above, the committee believes that three key technology issues inherent in the ONR 351 UAV/UCAV vision and plans have broad implications well beyond the confines of that specific vision:

1. Software engineering,
2. Autonomy, and
3. Network-centric operations.

Software Engineering

One of the primary attractions of adding UAV/UCAV technology to the naval force structure is that it can be much less expensive than other options such as crewed aircraft and single-use cruise missiles. For example, the DARPA/Air Force UCAV program is aiming for a unit cost one third that of the Joint Strike Fighter. Historically, aircraft cost has been proportional to takeoff weight, and UAV/UCAVs are projected to be significantly smaller than current tactical aircraft. However, avionics now account for 30 to 40 percent of the development cost of a new tactical aircraft, and a significant portion of the avionics development cost is accounted for by the software. While UCAV avionics requirements are different from those of crewed vehicles (autonomous functions replace human-machine interfaces, for example), they are not necessarily less expensive. Thus, unless the avionics and software development costs can be dramatically reduced, they could consume the entire UAV/UCAV development budget.

In the context of UCAVs, software engineering offers the 6.1 and 6.2 research communities a challenge and a real opportunity. The challenge is that without significant improvements in the software cost drivers—such as integration, verification, and reliability—UAV/UCAV may lose its attractiveness as a potentially low-cost force augmentor. The opportunity is that never before has a program concept been more dependent on new software engineering paradigms or more receptive to their introduction.

Technical areas in software engineering that are of specific interest to UAV/UCAV or that present targets of opportunity include the following:

- Model-based software engineering,
- Software maintenance and revalidation, and

- Software integration.

Model-based software refers to formal, semiautomated methods used to derive software-level requirements from system-level models (the models referred to are heuristic rather than physics-based). Another approach to the same problem might entail very high level, highly dynamic, and self-adaptive programming techniques.

Software maintenance and revalidation are always needed since fielded software requires continual updating to correct problems and enhance capabilities. Validation is extremely lengthy and costly compared with the time and costs of evolving microelectronics hardware.

Problems associated with software integration are the driver for many of these difficulties. These problems have been exacerbated by the fundamental change in the role of avionics software: from being a federation of relatively simple control loops it has become a fabric that keeps the aircraft together.

Also, the replacement of the pilot by autonomous software offers an opportunity to rearrange the partitions between avionics and decision making, since they are now all part of one large software system.

These are very hard technical problems, problems that have been attacked many times with only limited success. They are not peculiar to UAVs/UCAVs, but the program's success is crucially dependent on their resolution. The continuing explosion of hardware capabilities may enable directions not hitherto practical.

What is needed is fundamental technical groundwork rather than just clever ad hoc fixes. Its importance to naval systems in general and to UAVs/UCAVs in particular implies that the entire Department of the Navy (not just ONR 351) should consider whether it has sufficient commitment to basic research in software engineering, especially in the 6.1 area.

The difficulty here is that while every operational program needs software, no such program wants to spend the time and money to acquire the fundamentals. This kind of basic research must be funded separately from the system and equipment developers while still maintaining close contact with them. The Navy should consider supporting basic efforts in this area and should ensure that they are closely coordinated with similar efforts across the DOD.

Autonomy

The Department of the Navy has signalled that it recognizes the potential importance of autonomous operations by establishing autonomous operations as an FNC. This FNC provides a focus for efforts to develop air, surface, and subsurface autonomous platforms that meet the need for extended, remote operations in high-risk settings. Many of the S&T issues underlying the operation of highly autonomous platforms are common across both platform environment and mission type.

There are currently no widely accepted definitions nor is there any structure for organizing the investigation of system autonomy. Because there is no common framework for describing levels of autonomy and the functionality required to support them, it is difficult to recognize how the general principles of autonomy could be applied in any of the prototype research systems as currently implemented. This lack of a common framework impedes the S&T development efforts of the Navy and the other Services in three ways:

- The requirements for autonomy and the corresponding scope and budget of the S&T effort to support autonomy are difficult to express.
- Specific goals for autonomy in different mission and platform settings are difficult to express across research areas, and progress toward those goals is difficult to assess.
- Duplication of effort and lack of research coordination reduces the effectiveness of the available funding.

The decision to employ a technology in a military system is based on the expectation that the technology will improve the lethality, survivability, or affordability of the system. Recognizing that the Navy S&T support for the autonomous operations FNC will need to quantify the expected benefits of this emerging technology, the committee recommends that ONR, aligned with the autonomous operations FNC, should develop a comprehensive framework for defining levels of autonomy and characterizing the functional elements and potential military

benefits of each of the levels of autonomy. Such a framework should be applicable to air, surface, and subsurface missions and platforms and would be a valuable contribution to the military. The committee also believes that ONR should consider developing and conducting a series of autonomy competitions and demonstrations based on naval missions and platforms in order to attract the attention of commercial suppliers and encourage them to address Navy problems.

As a result of the rapidly growing commercial interest in software systems with high levels of autonomy, the Navy S&T programs in autonomy are not state of the art. Given the large commercial investments, neither the Navy nor any other Service is likely to achieve a leading position in S&T to support autonomous operations. It is clear that few, if any, of the fundamental issues in autonomous systems are unique to the Navy. However, the committee believes that the Navy should remain a participant in this technology area so that it will be able to leverage promising technologies as they emerge.

It is unlikely that commercial developers of autonomous system software and hardware will be motivated to apply their technology to Navy platforms and missions without substantial encouragement from the Navy. This encouragement might take the form of small-scale demonstration opportunities with broad participation and modest funding for the participants. A good example of such a demonstration environment is the annual week-long unmanned underwater vehicle exercises conducted by the Naval Oceanographic Office for unmanned tactical oceanography vehicles.

In addition, the committee believes that ONR should consider developing and conducting a series of autonomy competitions and demonstrations based on naval missions and platforms. The competitions and demonstrations should facilitate participation by small businesses and academia by offering modest funding to cover some of the costs of their participation. In this way, ONR could adapt emerging technology to naval needs without necessarily developing new technology.

Network-Centric Issues

The Chief of Naval Operations (CNO) recently declared that the Navy would be shifting its operational concept from one based on platform-centric warfare concepts to one based on network-centric warfare concepts. Network-centric operations (NCO), in this concept, are military operations that exploit state-of-the-art information and networking technology to integrate widely dispersed human decision makers, situational and targeting sensors, forces, and weapons into a highly adaptive, comprehensive system to achieve unprecedented mission effectiveness.⁵

The Navy, in conjunction with the Marine Corps, is moving rapidly to implement NCO. UAVs will become vital elements in future NCO since they will deploy situational and targeting sensors and weapons (in the case of UCAVs) and—depending on the degree of autonomy that is possible and authorized—will be part of the decision-making process.

Unfortunately, the implications of this shift to network-centricity have not yet been addressed explicitly in ESG's and N85's requirements and plans. It is into this gap that ONR 351 has jumped with its cooperating swarms of UAVs/UCAVs and its excellent analysis of the issues surrounding communications and dynamic networking. However, although ONR 351 described its vision as being network-centric, and many of the implied technical issues were treated, it used the term network-centric superficially and failed to address many other NCO-related issues, constraints, or requirements in a substantive manner.

For example, ONR 351 implied that the UAV/UCAV swarms would operate as a world unto themselves, communicating and cooperating only with each other. However, any ONR program in UAV/UCAVs will need to address how they would be integrated with and operate within a global naval network architecture connecting all sensors, weapons, forces, and command and control structures.

⁵Naval Studies Board, National Research Council. 2000. *Network-Centric Naval Forces: A Transition Strategy for Enhancing Operational Capabilities*. National Academy Press, Washington, D.C., p. 1

UAVs/UCAVs would incorporate highly sophisticated sensor subsystems capable of detecting and tracking targets of interest and of observing damage to attacked targets. Such information is critical to decision makers outside the postulated UAV/UCAV community of autonomous vehicles and will need to be provided in real time from the UAV platforms through the NCO network.

Since the airspace within which UAVs/UCAVs operate will need to be deconflicted using other operational air vehicles and missiles, the command control structure will need to be given the instantaneous location of deployed UAVs/UCAVs via the NCO network. The control of UAVs/UCAVs by ship-based and land-based commanders will also be implemented via the NCO network. Initially, such control will be teleoperative; that is, commanders will transmit very detailed instructions for flight path, maneuvers, and weapon release, but as the vehicles become more capable, trustworthy, and autonomous, only high-level commands will need to be transmitted. As UAVs/UCAVs become more autonomous and start to operate in cooperative swarms, the deconfliction challenge will become increasingly difficult.

The committee believes that all Navy UAV/UCAV programs, and the ONR 351 program in particular, must address all of these challenges, using the considerable wide-bandwidth capabilities of the naval NCO network to do so.

GENERAL CONCERNS

The committee had the following general concerns:

- Unmanned aerial vehicles appear to have very little requirements leadership in the Department of the Navy. The current leadership offered by the responsible Navy Department organizations seems to move slowly, envisions only relatively near-term scenarios, and is currently supporting independent multiple thrusts, as yet uncoordinated, without a clear unifying focus on the full potential of UAVs.
- A Department of the Navy UAV/UCAV master plan is needed that is more comprehensive than the current Naval UAV ESG plan. It should include S&T components as well as system concepts that explicitly acknowledge the existence of other UAV/UCAV plans and programs outside the Department of the Navy.
- UAV S&T coordination across the DOD community is inadequate. In addition, a Department of Defense S&T roadmap for UAVs is needed, perhaps as a supplement to the current OSD UAV master plan. Stimulated by the campaign in Kosovo and targeted for completion in June 2000, the current OSD plan does address DOD-wide scheduling and funding roadmaps for the accelerated fielding of UAVs but does not explicitly address S&T issues.
- Software development and cost are an increasingly critical issue for all complex computer-based systems. While everybody uses software, few, if any software organizations are responsible (or funded) for the creation of the much-needed software development tools and techniques.
- There seem to be no systematic approaches or tools available for partitioning functions between various machines (e.g., platforms, flights, C4ISR nodes) and human beings or for assessing the military benefits of autonomy. The mathematical and engineering sciences on which to base autonomous system design and evaluation need development. Autonomy is crucial, and the military will have to invest to exploit and extend what the private sector develops.
- Network-centric compatibility must be an integral part of any Department of the Navy UAV/UCAV future vision. Requirements must be worked up in the context of a true system-of-systems architecture, and there must be freedom to adjust the rest of the force structure to take advantage of UAV/UCAV contributions.

Appendixes

A

Committee Biographies

Frank A. Horrigan (Chair) retired in September 1999 from the Technical Development Staff for Sensors and Electronic Systems at Raytheon Systems Company. He has broad general knowledge of all technologies relevant to military systems. Dr. Horrigan, a theoretical physicist, has more than 35 years' experience in advanced electronics, electro-optics, radar and sensor technologies, and advanced information systems. In addition, he has extensive experience in planning and managing IR&D investments and in projecting future technology growth directions. Dr. Horrigan once served as a NATO fellow at the Saclay Nuclear Research Center in France. Today he serves on numerous scientific boards and advisory committees, including the NRC's Army Research Laboratory Technical Assessment Board and its Naval Studies Board.

Philip S. Anselmo is currently an executive with the Electric Sensors and Systems Sector of Northrop Grumman Corporation in Baltimore, Maryland, following a career with the U.S. Navy during which he achieved the rank of Rear Admiral. His present activities include development of intelligence, surveillance, and reconnaissance (ISR) programs for all the Services, and he works closely with the National community to extend its robust capability to real-time targeting problems. Admiral Anselmo, who is a naval aviator, possesses a diverse naval operational background, particularly in aviation and air warfare. His career includes commanding the USS *Kansas City* and USS *Constellation*. (Most of his early operational duties, however, included tours in fighter squadrons and carrier air wing groups.) Admiral Anselmo retired in 1995 as the Chief of Naval Operations' Deputy Director for Space and Electronic Warfare.

Willard R. Bolton is deputy technical director for the Atmospheric Radiation Measurement-Unmanned Aerospace Vehicles (ARM-UAV) program, a DOE collaboration involving industrial, academic, and national laboratory participation, and manager of the Exploratory Systems Technology Department at Sandia National Laboratories, Livermore, California. The ARM-UAV program was established to investigate the interaction of clouds and solar energy in the atmosphere and to demonstrate the utility of UAVs for atmospheric research by, for example, making radiative flux measurements over cirrus clouds and by providing data for comparison with satellite-derived radiative fluxes. He has an extensive background in aerodynamics, particularly in regard to UAV stability and control. Prior to joining Sandia, he was an engineer at the Boeing Military Airplane Division. His professional experience, which is in both technical management and program management, has included responsibility

for a number of advanced development and exploratory projects in areas ranging from parachute aerodynamics to high-speed water, ice, and earth penetration to suborbital missile payloads.

Thomas J. Cassidy, Jr., a retired Rear Admiral, U.S. Navy, is president and CEO of General Atomics Aeronautical Systems, a company that manufactures and supports UAV systems. Admiral Cassidy has a strong background in UAVs, particularly in regard to their S&T demands and operational needs. Prior to joining General Atomics in 1987, Admiral Cassidy served as a naval aviator for 34 years; his command duties included the Naval Air Station at Miramar, California, and the Pacific Fleet Fighter and Airborne Early Warning Wing. Admiral Cassidy also served on the Joint Chiefs of Staff and as director of Tactical Readiness for the Chief of Naval Operations. He is an associate fellow of the Society of Experimental Test Pilots. He also serves on the board of directors of the San Diego Aerospace Museum.

Robert W. Day is director of Programs and Analysis for the Raytheon Systems Company. His background is in combat C4I systems. Mr. Day joined the Raytheon Company when it merged with the Hughes Aircraft Company, where he was deputy manager of Defense Systems. (The principal product lines of Defense Systems were medium-range surface-to-air missile systems, theater missile defense systems, and battlefield systems.) Mr. Day served in the U.S. Navy for 26 years, during which time he flew A-6 aircraft combat missions in both Vietnam and Libya. Ashore, Mr. Day served at the Space and Naval Warfare Command, where he coordinated multiple program efforts in C4I with the Office of Naval Research. His last Navy assignment was as director of Stealth and Counter-Stealth Technology, where he was responsible for all technology developments, testing, technology transfer, security, export policy, and inter-Service contacts in the area of stealth and counterstealth.

Alan H. Epstein is R.C. Maclaurin Professor of Aeronautics and Astronautics, head of the Division of Propulsion and Energy Conversion, and director of the Massachusetts Institute of Technology Gas Turbine Laboratory. He received his degrees in aeronautics and astronautics from MIT, finishing with a Ph.D. in 1975, and has been on the faculty there since 1980. His technical interests focus on energy conversion, propulsion, and turbomachinery, including micro heat engines, unsteady flow in turbomachinery, turbine heat transfer, advanced instrumentation, hydroacoustics, and the application of active control to aeropropulsion systems. He is an active consultant to the gas turbine and aerospace industries. His awards include four Best Paper awards from the International Gas Turbine Institute and the ADME Gas Turbine Award. He is a member of the NRC Air Force Science and Technology Board. Professor Epstein is a fellow of the American Institute of Aeronautics and Astronautics and a member of the National Academy of Engineering.

Roger E. Fisher is director for Department of Defense Programs at Lawrence Livermore National Laboratory. In this capacity, he works with other laboratory directorates to support the Department of Defense and ensure that the laboratory is meeting national security needs, especially in the area of nonnuclear defense technologies. Dr. Fisher's research background is in advanced weapon and strike systems, with a focus on maneuverability and penetration issues. From 1994 to 1996, he served as deputy assistant secretary for research and development in the Office of the Assistant Secretary for Defense Programs at the Department of Energy (DOE). Prior to joining DOE, he was assigned to the Office of the Secretary of Defense, where he managed the Department of Defense strategy for improving precision strike warfare. Dr. Fisher has held numerous senior government positions throughout his more than 30-year career, including science advisor for the U.S. Third Fleet and advanced technical advisor to the Chief of Naval Operations. Dr. Fisher's interests include aerodynamics. He is an FAA-certified commercial pilot.

Ray "M" Franklin is a retired U.S. Marine Corps Major General who once headed the Marine Corps R&D effort. Today, General Franklin serves as a defense consultant, primarily on issues of amphibious warfare and force projection. He is particularly knowledgeable about research and development (6.2 through 6.4), systems acquisition, and military operations such as amphibious warfare. A naval aviator, General Franklin has experience in both rotary- and fixed-wing aircraft. He has participated in studies for the Naval Research Advisory Committee (countermine capabilities and littoral warfare).

Norman D. Geddes is president at Applied Systems Intelligence, Inc. (ASII). ASII provides support for the defense community and NASA, as well as commercial artificial intelligence applications for the aerospace and transportation industries. Dr. Geddes's research background is in intelligent control systems, particularly in decision aiding methods for automated vehicles. He has played a key role in the development and application of intelligent user interfaces based on artificial intelligence principles, including the modeling of human operator intentions. He is a graduate of U.S. Navy pilot training and an experienced tactical jet fighter pilot. Prior to his work in intelligent decision aiding, Dr. Geddes was director of system development for GEC Marconi Avionics. His professional society memberships include the American Institute of Aeronautics and Astronautics and the Institute of Electrical and Electronics Engineers.

Robert H. Gormley, a retired Rear Admiral, U.S. Navy, is president of The Oceanus Company, a technology advisory firm serving U.S. and foreign clients in aerospace, defense, and electronics. His expertise is in the technologies that impact airborne reconnaissance systems, unmanned aerial vehicles (UAVs), vertical/short take-off and landing aircraft, weapon system combat survivability, military requirements formulation, and test and evaluation planning. In addition to his duties at Oceanus, Admiral Gormley serves as consultant to the DARPA/USAF UCAV program office. As a former career naval officer and aviator, Admiral Gormley commanded the aircraft carrier USS *John F. Kennedy* as well as an air wing and fighter squadron during the Vietnam War. He also served in the Navy's Operational Test and Evaluation Force, Office of the Assistant Secretary of Defense (systems analysis), and as chief of studies, analysis, and war gaming for the Joint Chiefs of Staff. Admiral Gormley participates in national security studies undertaken by the NRC and has been a member of study panels of the Defense Science Board and the Naval Research Advisory Committee.

Harry W. Jenkins, a retired Major General, U.S. Marine Corps, is director of Business Development and Congressional Liaison at ITT Industries-Defense, where he is responsible for activities in support of tactical communications systems and airborne electronic warfare between the Navy, Marine Corps, National Guard, and appropriate committees in Congress. His operational background is in expeditionary warfare, particularly its mission use of C4I systems. During Operation Desert Storm, General Jenkins served as the Commanding General of the Fourth Marine Expeditionary Brigade, where he directed operational planning, training, and employment of the ground units, aviation assets, and command and control systems in the 17,000-man amphibious force. General Jenkins's last position before retirement from the U.S. Marine Corps was director of expeditionary warfare for the Chief of Naval Operations, where he initiated a detailed program for C4I system improvements for large-deck amphibious ships and reorganized the Navy's UAV efforts for operations from aircraft carriers and amphibious ships. He is a member of numerous professional societies, including the Navy League and the Aerospace Industries Association.

James D. Lang recently retired from the Boeing Company Phantom Works. Dr. Lang is an expert in autonomous vehicles, particularly in regard to issues of coordination. His 11-year service with Boeing (and McDonnell Douglas) followed 24 1/2 years of service with the U.S. Air Force. His career involved engineering and R&D management, university teaching and research, flight test engineering, and flying duties as a command pilot and engineering test pilot. Dr. Lang is currently a member of the DARPA/U.S. Air Force/Boeing National Technical Advisory Board for the UCAV program; an ad hoc member of the U.S. Air Force Scientific Advisory Board; a consultant to the Ohio Aerospace Institute; an originator of a multidisciplinary university and industry research effort in dynamic lift; and a reviewer for NASA proposals and American Institute of Aeronautics and Astronautics design competitions. Dr. Lang has authored or coauthored 41 technical publications, including the textbook *Aircraft Performance, Stability, and Control*. He was elected as fellow of the Royal Aeronautical Society (England) in 1996.

Joseph B. Reagan is retired vice president and general manager of research and development at Lockheed Martin Missile and Space and was an officer of the Lockheed Martin Corporation. A member of the National Academy of Engineering, he has a strong background in defense technology development, particularly in space

and missile technologies. Dr. Reagan joined Lockheed nearly 40 years ago as a scientist. He led the Space Instrumentation Group for 10 years and was responsible for the development and on-orbit deployment of over 20 scientific payloads for NASA and the Department of Defense. His research interests included space sensors, radiation belt and solar particles, nuclear weapon effects, and the effects of radiation particles on spacecraft systems. As general manager of the R&D Division, he led over 750 scientists and engineers in the development of advanced technologies in the fields of optics, electro-optics, information software, cryogenics, guidance and controls, electronics, and materials. Today, Dr. Reagan is a director on the board of Southwall Technologies, Incorporated, a high-technology company specializing in the manufacture of thin-film coatings for high-performance residential, industrial, and automotive windows. He is also a director on the board of the Tech Museum of Innovation, where he is the chairman of the Education Committee. He is involved in numerous activities that foster the improvement of science and mathematics education in the United States. Dr. Reagan is a fellow of the American Institute of Aeronautics and Astronautics and is vice chair of the Naval Studies Board.

John P. Retelle, Jr., is manager of business development at Logicon Advanced Technology, a subsidiary of Northrop Grumman Corporation. Dr. Retelle's background is in airborne artificial intelligence, aeronautics, and advanced computing. His professional career of more than 30 years spans a wide range of senior positions in both industry and government. He began as a flight test engineer for the U.S. Air Force, where he conducted flight tests and simulations in transonic aircraft technology. Dr. Retelle also served as an associate professor at the U.S. Air Force Academy and as a program manager at DARPA. While at DARPA, he provided technology and program direction for advanced technology demonstrations in airborne artificial intelligence (Pilot's Associate) and aircraft design (X-29, X-31). Dr. Retelle recently served as president of PAR Government Systems Corporation, where he transitioned PAR's expertise in computing and sensor R&D to new information-intensive products beyond traditional Department of Defense markets. Dr. Retelle is a certified commercial pilot and a member of several professional societies, including the American Institute of Aeronautics and Astronautics and the Institute of Electrical and Electronics Engineers.

Howard E. Shrobe is associate director and principal research scientist at the Massachusetts Institute of Technology Artificial Intelligence Laboratory (MIT AIL). His research is in intelligent systems, particularly in knowledge-based software development. From 1994 to 1997, Dr. Shrobe served as assistant director and chief scientist of the DARPA Information Technology Office, where he was responsible for two programs: the Evolutionary Design of Complex Software and Information Survivability. At the MIT AIL, Dr. Shrobe's research efforts include knowledge-based collaboration, dynamic domain architecture, and intelligent information infrastructure projects.

John F. Walter is program area manager for the Strike Warfare Program Office of the Power Projection Systems Department at Johns Hopkins University Applied Physics Laboratory (JHU/APL). Dr. Walter's background is in precision strike weapons and associated autonomous support systems. His previous positions at JHU/APL included project manager for the Tomahawk Land-Attack Project and technical area manager for autonomous flight control systems for the Harpoon Missile. Dr. Walter's research interests include laser physics, propagation, electro-optics, inertial navigation, and missile guidance. He is a member of the American Institute of Aeronautics and Astronautics and the Precision Strike Association Board of Directors.

B

Terms of Reference

In response to a request from the Office of Naval Research, the National Research Council established the Committee for the Review of ONR's Uninhabited Combat Air Vehicles Program, under the auspices of the Naval Studies Board, to conduct a study as follows:

An assessment of the science and technology issues relating to the Office of Naval Research's (ONR) program for uninhabited combat air vehicles (UCAV) will be conducted. The review will evaluate ONR's UCAV technology activities, including vision documents and science and technology roadmap (in areas of vehicle dynamics, communications, sensors, and autonomous agents) against criteria which the committee will select such as the relevance for meeting future naval priorities, cost and time scale for utilization, duplication of effort, and scientific and technical quality.

C

Acronyms and Abbreviations

ACTD	advanced concept technology demonstration
ATD	advanced technology demonstration
ATR	automatic target recognition
BAA	broad agency announcement
BDA	battle damage assessment
BM	battle management
CAP	combat air patrol
C4ISR	command, control, communications, computing, intelligence, surveillance, and reconnaissance
C4ISRT	command, control, communications, computing, intelligence, surveillance, reconnaissance, and targeting
CNO	Chief of Naval Operations
COTS	commercial off-the-shelf
DARO	Defense Airborne Reconnaissance Office
DARPA	Defense Advanced Research Projects Agency
DCGS	distributed common ground system
DOD	Department of Defense
DTS	Deployed Transit System
EO	electro-optical
ESG	Executive Steering Group
FNC	future naval capability
FLIR	forward-looking infrared
FWV	fixed-wing vehicle

GPS	Global Positioning System
HAE	high-altitude endurance
IHPTET	integrated high-performance turbine engine technology
IPT	integrated product team
IR	infrared
LAN	local area network
MAE	medium altitude endurance
MASINT	measurement and signature intelligence
MCCDC	Marine Corps Combat Development Command
MCM	mine countermeasures
MRE	multirole endurance
MSTAR	Moving and Stationary Target Acquisition and Recognition (program)
MTI	moving-target indicator
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NCO	network-centric operations
NIMA	National Imagery and Mapping Agency
NRC	National Research Council
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
OSD	Office of the Secretary of Defense
P3I	preplanned product improvement
PEO (CU)	Program Executive Office for Cruise Missiles and UAVs
R&D	research and development
RECCE	reconnaissance
RF	radio frequency
RPV	remotely piloted vehicle
RSTA	reconnaissance, surveillance, targeting, and attack
RW	rotary wing
S&T	science and technology
SAR	synthetic aperture radar
SEAD	suppression of enemy air defense
TCS	Tactical Control Station
TDA	technology development approach
T&E	testing and evaluation
TES	Tactical Exploitation System (Army)
TOF	time of flight
TUAV	tactical uninhabited aerial vehicle

UAV	unmanned aerial vehicle
UCAV	uninhabited combat air vehicle
UGV	unmanned ground vehicle
USAF	U.S. Air Force
VSTOL	vertical short takeoff and landing
VTOL	vertical takeoff and landing
VTUAV	vertical takeoff and landing tactical uninhabited air vehicle
WAN	wide area network
WPN	weapons procurement, Navy